Exposure of Air Breathing Engines to Nuclear Dust Environment. Volume 3. Performance Deterioration of a Second F100 Turbofan Engine Upon Exposure to a Simulated Nuclear Dust Enviro...

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Exposure of Air Breathing Engines to Nuclear Dust Environment (U)

Volume III—Performance Deterioration of a Second F100 Turbofan Engine Upon Exposure to a Simulated Nuclear Dust Environment (U)

Michael G. Dunn
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January 1991

Technical Report

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13. ABSTRACT *(Maximum 200 words)*

[redacted] Results are reported for a measurement program designed to determine the performance behavior of an operational F100 turbofan engine when exposed to a simulated nuclear dust environment. This is the second F100 engine in a series of two to be exposed to the same environment. The features of this experiment that distinguish it from the previous F100 measurement program are that the dust concentration was relatively high (500 mg/M^3 or 5×10^{-7} gm/cm^3) and the engine was operated at elevated turbine inlet temperatures ($\sim$2400°F). Engine parameters were sampled at 5 second intervals throughout the dust exposure in order to help in recognition of incipient engine difficulties. A successful effort was made to develop a technique that could be used to extend the useful life of a severely damaged engine.

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PREFACE

(This Preface is UNCLASSIFIED)

The work described in this report was performed by the Calspan Corporation under support of the Defense Nuclear Agency (DNA), Contract No. DNA 001-83-C-0182. The work was conducted during the period 1 August 1989 to 15 January 1990. The activity reported herein was part of a broad technology development program which is still in progress under the above contractual support by DNA.

The author would like to thank the DNA Technical Monitor, Major Vayl Oxford/SPWE, for many helpful discussions and suggestions during the course of this work. The author would especially like to express his appreciation to Mr. James C. Moller for his many contributions to this program. Mr. Moller returned to graduate school at Rensselaer Polytechnic Institute to pursue a PhD degree just prior to the writing of this report. However, he contributed a significant portion of the results reported herein prior to his departure. The outstanding contributions of the Calspan ATC technicians who were involved in this program are also gratefully acknowledged. In particular, we would like to express our appreciation to Mr. Mario Urso, Mr. Jeffrey Barton, and Mr. Robert Field who have substantially contributed to the performance of the measurements reported here.

We would also like to express our appreciation to the crew at Kelly Air Logistics Center who, under the direction of Mr. Donald Hill, performed the post-test disassembly and photography of the engine described herein. This work was performed in a very timely manner under extreme pressure.

CONVERSION TABLE

(This Table is Unclassified)
Conversion factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET
TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	giga becquerel (GBq)*
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_K = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)**
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbf avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter^2 (kg·m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	Gray (Gy)**
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22 X E -1	kilo pascal (kPa)

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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Section 1
(U) INTRODUCTION

(U) For the past several years a technology program has been ongoing at Calspan in the area of gas turbine propulsion research that utilizes a unique facility and a unique experimental technique which allows one to subject operating engines to adverse environments without endangering either an airplane or a flight crew. Testing has now been completed on two F100 engines. The results of the first test series were reported in Reference 1.[1] The dust concentrations used in that measurement program and the power settings were designed to determine glassification threshold temperature and erosion tolerance of the engine. The experiment was very successful in achieving these goals. This report deals exclusively with a description of a second experiment designed to test the response of another F100 turbofan exposed to the same dust mixture as the first engine but while operating at a dust concentration and at a turbine inlet temperature (TIT) sufficiently high to emphasize glassification and minimize compressor erosion. The appropriate test conditions at which to operate were determined on the basis of data obtained from a combustor-simulator experiment described in Reference 2[2] and from the measurements described in Reference 1.

(U) Reference 1 presents a summary of the previous engine measurement programs performed at Calspan and cites the specific references in which a more detailed description of the experiment and the results can be found. The reader is referred to that report since this report will be an extension of Reference 1. In all of this work the basic theme has been to identify which of the engine parameters available to the flight crew provide an early warning of impending problems and to determine how the crew should cope with the problem in order to maximize engine life under the conditions encountered.

(U) In the remainder of this report, the experimental technique will only briefly be described in Section 2 (it was described in depth in Reference 1), the results of

1. (U) Dunn, Michael G., "Exposure of Air Breathing Engines to Nuclear Dust Environment, Volume I—Performance Deterioration of an Operational F100 Turbofan Engine Upon Exposure to a Simulated Nuclear Dust Environment (U)," Calspan Report No 7170-8, January 1991, DNA-TR-90-72-V1, (SECRET).
2. (U) Moller, James C. and Dunn, Michael G., "Exposure of Air Breathing Engines to Nuclear Dust Environment, Volume II—Dust and Smoke Phenomenology Testing in a Gas Turbine Hot Section Simulator (U), Calspan Report No 7170-10, January 1991, DNA-TR-90-72-V2, (UNCLASSIFIED).

the measurement program will be presented in Section 3, and the conclusions and recommendations will be presented in Section 4.

Section 2
(U) EXPERIMENTAL TECHNIQUE

(U) The Large Engine Research Cell (LERC) at Calspan was the facility in which the measurements described herein were conducted. This unique device and the associated dust injection system were both previously described in Reference 1 and other documented references. However, it is appropriate to briefly summarize this facility which is an air cooled noise suppression system capable of silencing high-thrust engines to the point where they can be operated in populated areas without complaint. The air cooled feature makes it difficult to determine from a distance whether or not the facility is in operation.

(U) The Dust Injection System (DIS) is a very important part of the test apparatus and was designed and built to achieve the objective of the engine measurements; the accurate regulation of the dust environment. The reader is referred to Reference 1 for a detailed description of this system.

(U) A detailed description of the F100 class of turbofan engine used in this measurement program was also given in Reference 1. The particular engine used here is S/N P680054 which indicates that it was the 54th engine off the assembly line. This engine, like the first engine tested (S/N P680071), uses an Arabic 1 compressor configuration. Current versions of this engine use an Arabic 3 configuration. The differences between the Arabic 1 and the Arabic 3 compressors should not influence the machine response to the dust environment.

(U) The F100 engine is a two-shaft turbofan engine which has a high augmentation afterburner (the afterburner was installed on the engine used here but was not activated). The bypass ratio for this engine is 0.7. The engine (with an overall compression ratio of 25) is modular in construction and is made up of a three-stage fan driven by stages 3 and 4 of the turbine, a ten-stage axial compressor driven by stages 1 and 2 of the turbine, an annular ram induction combustor (thirteen fuel nozzles) with full louver construction and contains two igniter plugs, and a multi-flap balanced beam articulated exit nozzle. The engine control system is a unified hydromechanical fuel and nozzle area control with digital electronic supervisory control. The engine-mounted digital computer provides vernier trim signals to the unified control

(UC) for precise control of HP rotor speed and engine airflow, and for control of low-pressure (LP) turbine inlet temperature, or high-pressure (HP) turbine discharge pressure whenever either becomes a limiting factor. The control schedules the compressor inlet variable guide vanes (CIVV) and provides trim signals to the UC to minimize fan rotor overspeed or underspeed. If a fan overspeed situation is detected, the control system reacts by opening the exhaust nozzle area and reducing fuel flow rate.

(U) While dust was being injected into the engine described here, there were three video cameras in operation; one looking at the inlet fan face, one looking at a profile view of the engine which allowed a clear view of the exhaust, and one looking at the tailpipe. Voice from the engine cab and from the control room was recorded in real time on the engine-profile camera. Detailed comments regarding engine behavior and instrumentation parameters were recorded along with the video in real time.

(U) A history of engine S/N P680054 is presented in this paragraph. The engine was shipped from Pratt/Whitney to Edwards AFB on 10 December 1973 after final acceptance. At the completion of 186.7 total operational hours, the fan drive turbine was replaced on 4 June 1975. The fan drive turbine was again replaced after 214.7 total hours of operation on 8 March 1976. At this same time, the inlet fan was also replaced. The fan drive turbine continued to be a problem and was replaced again on 14 September 1979 after 349.5 total hours of engine operation. This fan was previously replaced after 214.7 total hours of engine operation and after 186.7 total hours of operation. The rear compressor drive turbine was also replaced during the maintenance of 14 September 1979. The inlet fan was once again replaced on 29 April 1981 after 498.3 total hours of operation on the engine (approximately 282 total hours of operation on the fan that was replaced at 216.9 hours). On 23 September 1981 both the fan drive turbine and the inlet fan were replaced again after 568.2 total hours of engine operation. On 7 July 1983 the engine was preserved and shipped to Calspan to be used for the measurement program described in this report. During its lifetime prior to arrival at Calspan, the engine had accumulated a total operating time of 584.3 hours of which 295.1 hours were flight time hours.

(U) The dust blend used for the second F100 engine was the same as that used for the first F100 engine. This blend was specified by RDA (G. Rawson) Reference 3[3] and is given in Table 1.

Table 1. (U) Definition of blend #2 used for S/N P680054.

Hollywood sand			
	premix recipe:	15% of	106 μm size bin
		85% of	106 μm to 250 μm size bin
Corona clay			
	premix recipe:	75% of	106 μm size bin
		25% of	106 μm to 250 μm size bin
New Mexico scoria			
	premix recipe:	100% of	250 μm size bin
Bentonite			
	as available	100% of	106 μm size bin

(UNCLASSIFIED)

(U) Mixing recipe of premixed materials above:
26% Hollywood sand + 26% Corona clay + 42% black scoria + 6% Bentonite

(U) A previous analysis as reported in Reference 1 was performed to determine that the glass fraction of the black scoria was 80 to 85%. Blend #2 was therefore constructed so that the mixture glass fraction was about 34%. Further, the melting temperature of black scoria is relatively low compared to the Mt. St. Helens material.

(U) The technique for injecting the dust blend into the air stream has been well documented in past reports. The overall experimental procedure has also been documented and the previous paragraphs have provided the appropriate references to this work.

3. (U) Rawson, G., "Private communication from G. Rawson (RDA consultant) to C. Padova (Calspan)," August 1985.

Section 3
(U) DISCUSSION OF RESULTS

(U) This section of the report will be presented in several sub-sections in an effort to provide the reader with as much detail as possible concerning the measurement program. The section begins with a description of the goals of the second F100 engine test, is followed in Section 3.2 with a description of the test matrix, the experimental procedure and pre- and post-test calibration data are presented in Section 3.3, the time histories of recorded engine parameters are described in Section 3.4, the event that terminated the test matrix is described in Section 3.5, and the results of the teardown are described in Section 3.6.

3.1 (U) Objectives for second F100 engine test.

(U) The objectives of this, the second of the F100 engines, were to test the response of the engine under conditions for which glassification of the dust material followed by deposition on the hot-section components was fully anticipated. The specific objectives that we wanted to achieve with this engine were to find answers to the following questions:

a. [redacted] Would the ingested material glassify and deposit on the hot-section components for the engine setting typical of a penetration flight plan? The previous F100 engine test (Reference 1) and the simulator test (Reference 2) both suggested that deposition would occur. However, it was not clear that a deposition condition would not occur above which the material would spall off the surfaces due to shear forces and temperature cycles.

b. [redacted] How far towards the surge line could the burner pressure and the HP compressor discharge pressure be pushed before a high speed surge would occur? We know from the previous F100 measurements that at elevated operating temperatures, these parameters increased with dust exposure time.

c. (U) Could the engine be cleaned in flight by rapid throttle movement if the cloud (dust ingestion) could not be exited? We were previously able to clear the engine (Reference 1) with the dust turned off.

d. [redacted] If the engine did encounter difficulty in operation and spooled down on its own or if it were shut down by the operator, would it subsequently re-start? We were unable to restart the first F100 engine after about 85 minutes and 60 kg of exposure. The post-test teardown of that engine suggested that difficulty in starting may have been due to either compressor erosion or deposition of material on the fuel nozzles. It is known that two aircraft have been able to restart their engines after in-flight shut down attributed to traversing volcanic clouds. In both cases, these aircraft were in the cloud for a very brief time before the engines shut down.

3.2 (U) Experimental procedure.

(U) Prior to exposing the engine to any dust, a set of baseline data runs was performed in order to be able to evaluate degradation due to the dusty environment. All of the available engine and test cell instrumentation were routinely recorded during both the calibration and dust-exposure runs as detailed in Reference 1. The operating procedure is also described in depth in Reference 1 and will not be repeated here.

3.3 (U) Test matrix for engine S/N P680054.

[redacted] A summary of the test conditions to which engine S/N P680054 was exposed is given in Table 2. This table illustrates that during the entire dust-exposure experiment, which lasted approximately 21 minutes, the dust concentration was held fixed at 500 mg/M^3 and the dust was never turned off. With the exception of the three times that the engine was cycled in an effort to clear the deposited material, the throttle was placed in a position so that the turbine inlet temperature would be on the order of 2480^{o}F to 2500^{o}F. As will be demonstrated in Section 3.4, many of the engine parameters were changing rapidly during dust ingestion. It is shown on Table 2 that matrix point #3 was intended to be a 12 minute exposure, but was terminated at 11.5 minutes. At the 11.5 minute point, an attempt was made to clear the engine by rapidly retarding and advancing the throttle. This technique had successfully been used on

Table 2. (U) Summary of dust exposure runs on second F100 engine (S/N P680054).

MATRIX PT. PT.#	DUST CONC. mg/M^3	DUST DURATION MIN.	SUMMATION OF EXPOSURE TIME MIN.	DUST INGESTED (THIS TEST) Kg	SUMMATION OF DUST INGESTED Kg	EPR	FTIT °F	TIT °F
1	500	3	3	6.32	6.32	2.6	1629	2485
2	500	6	9	12.64	18.96	2.6	1629	2485
3	500	11.5 *	20.5	24.23	43.19	2.6	1629	2485

* This run was intended to be 12 min. duration, but was terminated at 11.5 min. for reasons to be discussed. Engine would not re-light after matrix pt. #3.

two earlier occasions in the test matrix, but on this third attempt the engine went into an uncontrolled surge mode and had to be shut down. Many unsuccessful attempts were made to restart the engine after the event just noted. Because the engine could not be started, it was shipped to Kelly AFB for teardown. The details of the event leading to termination of the test program and the results of the teardown will be described in depth later in this section.

[redacted] Table 2 indicates that the total amount of dust material ingested by the engine during the test matrix was 43.19 kg. The previous F100 engine tested during this measurement program ingested 59.46 kg of dust material and operated for 84.92 minutes before it could no longer be operated. The principal differences between the test matrices for the two engines were that the second engine operated at sustained higher dust loading while operating at higher turbine inlet temperatures. The result of this is that the principal damage mechanism for the first engine was compressor erosion while for the second engine the principal damage mechanism was glassification and subsequent deposition of the glassy material on the hot section components.

3.4 (U) Time-history of recorded engine parameters.

(U) As previously noted, the engine paramaters were sampled at 5 second intervals and the raw data were stored for later processing on an IBM PC. When processing the data for presentation here, the format in which the engine unified control system would use these data was kept in mind so that the data could be presented in a consistent manner.

[redacted] Near the completion of the test series reported in Reference 1, it was determined that the deposited glassy material could be cleared from the engine by rapidly accelerating and decelerating the engine. If this were done, then the burner pressure, the compressor discharge pressure, the fan inlet total temperature, the fuel weight flow, and the engine air weight flow would all return to values near their respective pre-dust exposure values. From an operational viewpoint, the advantage of this rapid throttle movement is that the engine can be cleared without significant loss of flight speed or altitude. As previously noted, one of the purposes of this test matrix was to determine how far this technique could be pushed.

[redacted] The results presented in Reference 1 demonstrated that at the dust concentration (500 mg/M^3) and the turbine inlet temperatures (2485°F) associated with this test series, the engine instrumentation would respond very quickly after initiation of dust ingestion to indicate that conditions within the engine were changing. Detailed time histories of many of these parameters were presented in Reference 1. The format in which the results for the second F100 engine will be presented is different than that used for the first F100 engine, but the essential features of the data are very similar.

(U) From the viewpoint of a flight crew, the most immediate indication of entry into a dust cloud is the presence of St. Elmo's fire on the windscreen and at the fan face of the engine. This glow at the engine fan face has been recorded on videotape in the laboratory and can be shown to occur immediately upon arrival of the dust at the fan face. For the experimental conditions of the test series reported here, the glow is very bright and easily seen under daylight conditions.

[redacted] Probably the second most easily observed indicator of the presence of the dust cloud at these high power settings is the increase in engine pressure ratio (EPR, P_{T_2}/P_{T_6}). Figure 1 is a time history of the engine pressure ratio. Before the dust was turned on, the throttle was set by the operator so that the engine was operating at an EPR of about 2.60. The dust was turned on at 13.2 minutes and an immediate increase in EPR is observed. The EPR increased steadily during the first four minutes of dust exposure at a rate of 0.3 per minute. After about six minutes of dust exposure, the burner pressure had increased to such a high value that it was prudent to attempt to clear what was thought to be deposited material from the engine. Therefore, at 19.3 minutes the throttle was rapidly cycled as can be seen from the data record of Figure 1. At the conclusion of the throttle excursions, the EPR was set by the operator to a value very near the initial value of 2.60. The flow of dust was not turned off during the entire test matrix. During the second period of dust ingestion, the EPR again increased steadily but at a slower rate (0.16 per minute) than during the first dust exposure period. At about 24.8 minutes, it again became necessary to clear the engine of deposited material as can be seen from Figure 1. Once again, the EPR was returned by the operator to near the pre-dust exposure value of 2.60. During the ensuing exposure period, the EPR increased steadily, until about 32.5 minutes. At 32.5 minutes, it became clear to the operators that the control system was taking over control of the engine and that it would again be prudent to clear the deposited material. Therefore, a third clearing attempt was initiated. We were unable to recover control

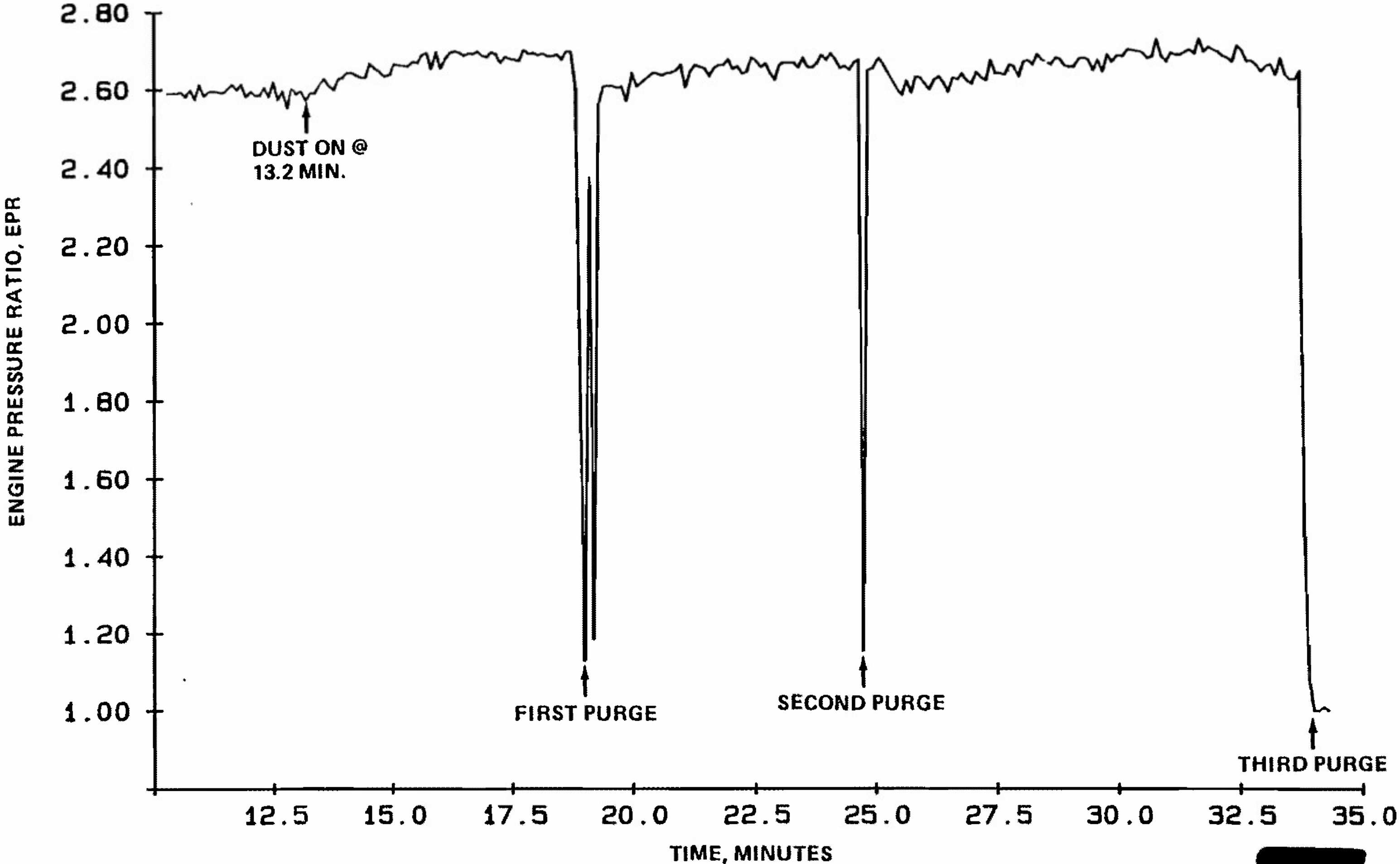


Figure 1. (U) Time history of engine pressure ratio (EPR).

of the engine during this event because the engine began to surge at a rate of twelve surges per second and an internal fire developed. A detailed description of this event will be presented in Section 3.5 after discussion of the recorded data.

[redacted] Figure 2 presents the overall compressor pressure ratio (P_{S_3}/P_{T_2}) as a function of time. Prior to turning on the dust, the engine was operating at a value of about 20.5. Relatively soon after the dust was turned on, the compressor discharge static pressure (P_{S_3}) began to increase rapidly with the ratio reaching a value of about 21.8 in less than a minute. The engine was then purged at 19.3 minutes as described in the preceding paragraph. When the throttle was adjusted to give an EPR of 2.60, the compressor ratio did not return to its pre-dust exposure value. However, it did return part way, followed by a rapid increase to the value at which the machine was operating near the end of the first exposure period. The throttle was again cycled at about 24.8 minutes and the EPR was returned to 2.60. This second throttle cycle had essentially no influences on the overall compressor pressure ratio at which the machine was operating as can be seen from Figure 2.

[redacted] Figure 3 presents the burner static pressure (P_b) divided by the compressor discharge static pressure (P_{S_3}) and represents one of the more interesting time histories that has been extracted from the data. The compressor dischrage static pressure (P_{S_3}) divided by the inlet total pressure (P_{T_2}) was just presented in Figure 2. The inlet total pressure is essentially constant during these experiments. The inlet total pressure was measured as was the weight flow of air which was also nearly constant as demonstrated in Figure 4. Therefore, the activity shown on Figure 2 is the result of increasing compressor discharge pressure and is not due to decreasing inlet total pressure. The ratio shown in Figure 3 is a figure of merit of the downstream loading on the compressor. Figure 3 illustrates that soon after the dust is turned on, the burner pressure begins to increase rapidly. It is quite possible for the burner pressure to become higher than the compressor discharge pressure without surging the engine because both of these quantities are static pressures and the flow velocities in the combustor are far lower than in the compressor exit nozzle. If burner pressure were taken to be nearly the gas stagnation pressure of the compressor, then the compressor exit Mach number would be 0.31 and such a number is certainly possible. During acceleration in the first purge shown on Figure 3, the pressure ratio reached 1.28 for a brief time without any surge or stall and then dropped to 0.61 for a brief period, followed by stabilization at the pre-dust exposure value of 0.99. This result was encouraging and

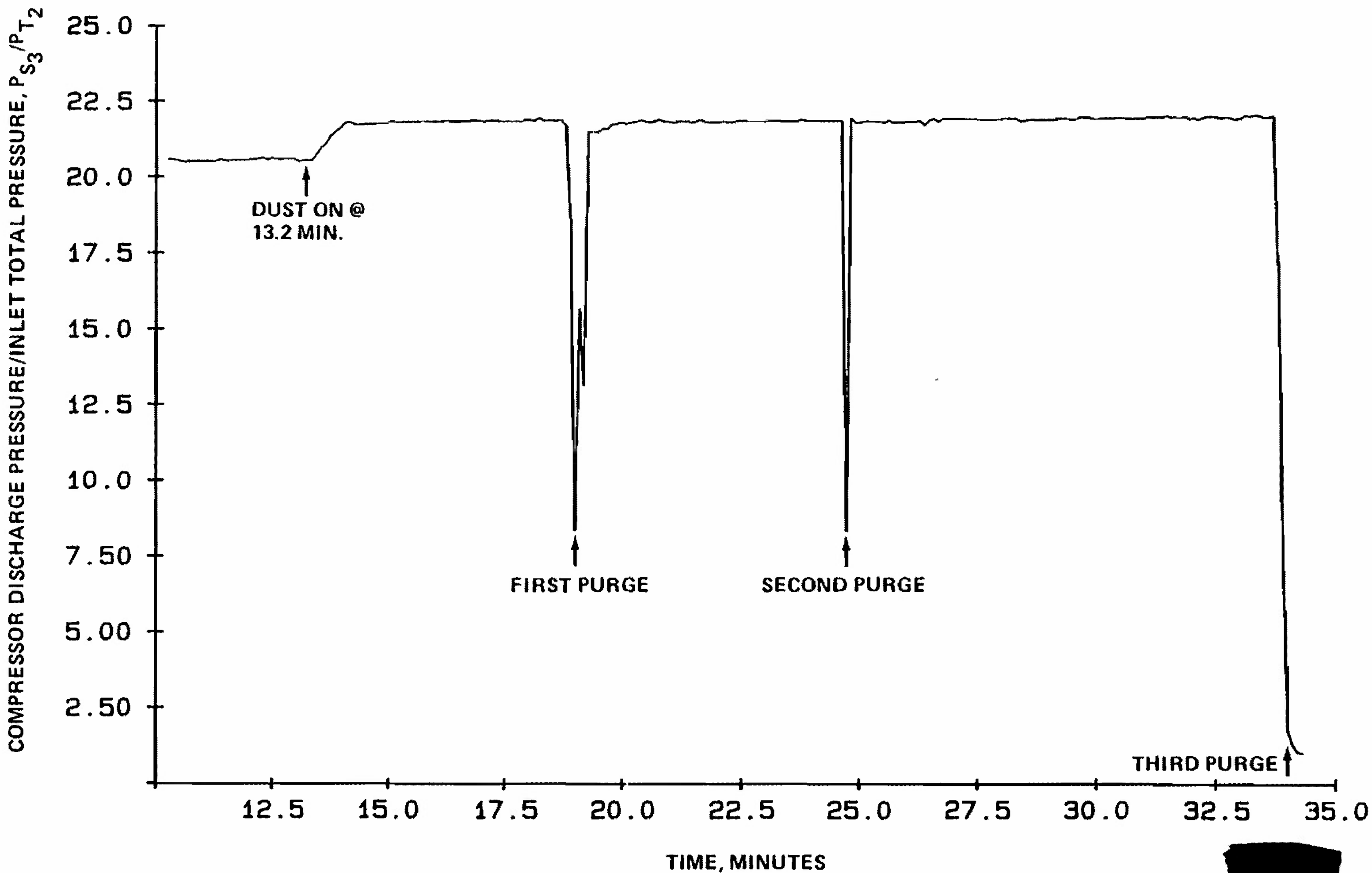
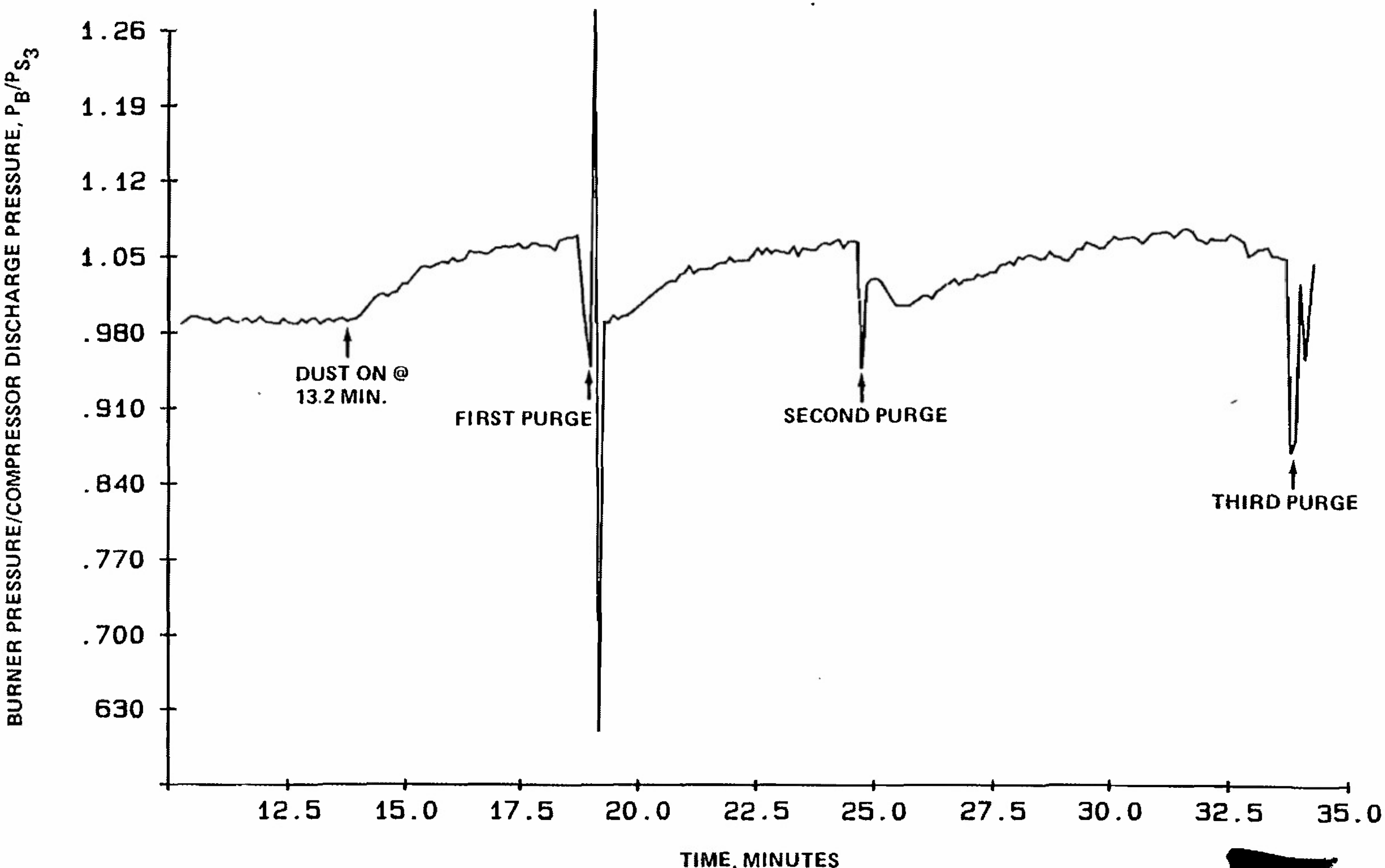


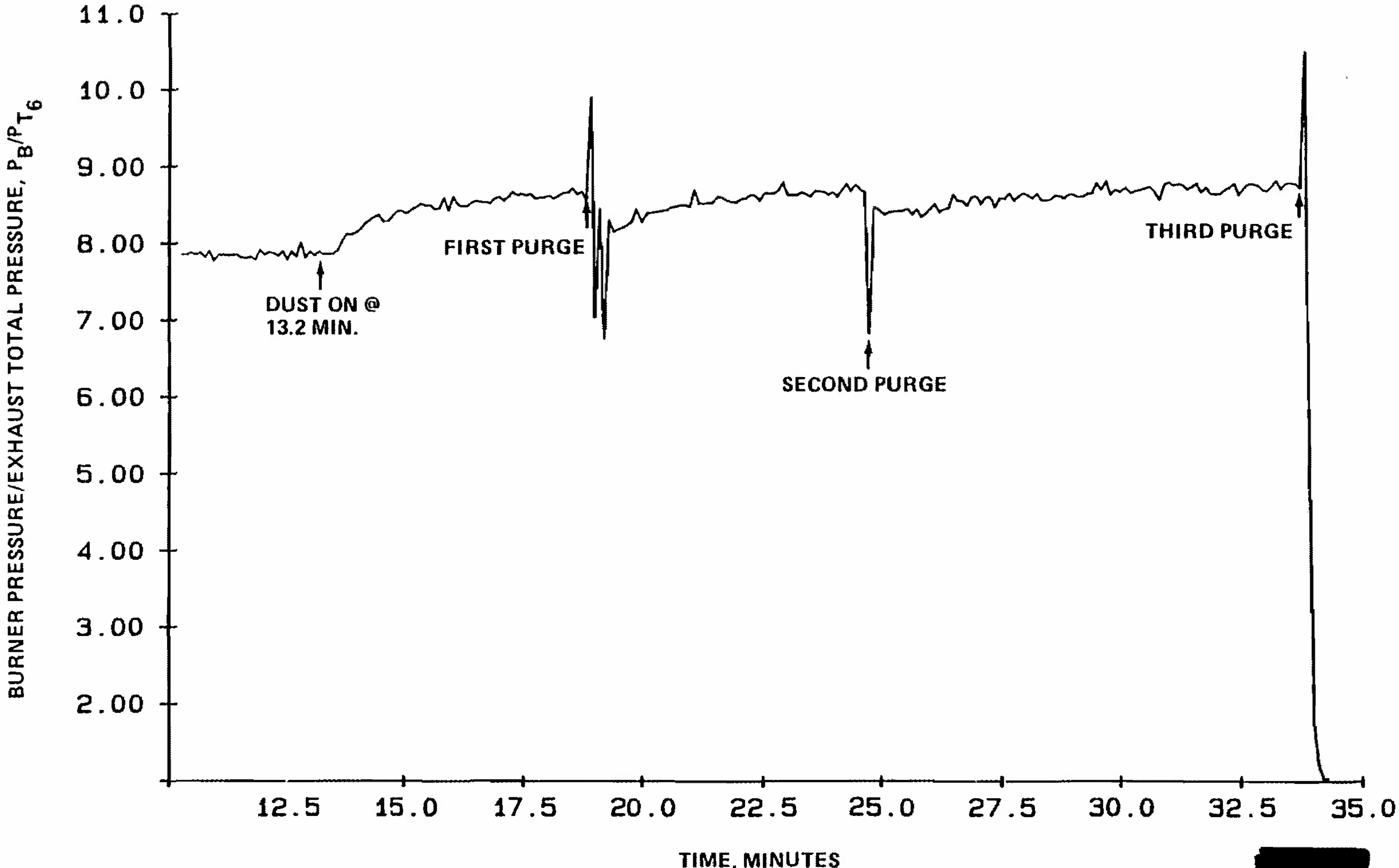
Figure 2. (U) Time history of overall compressor pressure ratio.



[redacted]

Figure 3. (U) Time history of the ratio of burner pressure to compressor discharge pressure.

[redacted]



[redacted]

Figure 4. (U) Time history of the ratio of burner pressure to turbine exhaust pressure.

[redacted]

it appeared that the engine had been successfully cleared without event. However, during the second exposure, the ratio again increased rapidly as it had done during the initial exposure. The engine was purged a second time, but the excursion in the pressure ratio was not as great as during the first purge. It is possible that the peak and valley may have been missed due to the five second sampling frequency of the data. The second purge was not as effective as the first in that the ratio did not quite return to the pre-dust exposure value of 0.99. The pressure ratio came sufficiently close to the pre-dust value that we were encouraged that the engine had been cleared. During both the first and second purges, a shower of material could be seen exiting the tail pipe. After the second purge, the ratio climbed again in a series of steps of about one-half minute in duration to a peak of 1.07. Near the end of the third exposure interval, the ratio levelled off and then fell to 1.05 just prior to the third purge. This behavior near the end of the third exposure period is consistent with the EPR data shown on Figure 1.

(U) Figure 4 presents the time history of the burner pressure normalized by the turbine exhaust pressure. The result shown on this plot is very similar to that shown on Figure 3 which was the burner pressure normalized by the compressor discharge pressure. These two figures suggest that the aerodynamic trends observed in the hot section region carry on through the exhaust system, which is as would have been anticipated.

[redacted] Figure 5 presents the time history of the corrected weight flow of air through the machine. The time at which the dust is turned on is marked on this figure as are the times of the three purges. During the first dust exposure period, there is a slight increase in air flow with increasing time. After both the first and second purges, the weight flow returned to the pre-dust exposure level. Also note that during the first minute or minute and one-half after the first and second purges, the character of the trace is very quiet. However, with increasing exposure time, activity on the data record suggests changing conditions within the engine.

[redacted] Figures 6 and 7 present the components of the compression system that make up the result presented in Figure 2. Figure 6 represents the compression of the high pressure compressor and Figure 7 represents the compression of the low pressure compressor. The high-pressure compressor pressure ratio increased by about 0.33 during the first one-half minute of dust exposure. The pressure ratio declined at a rate of

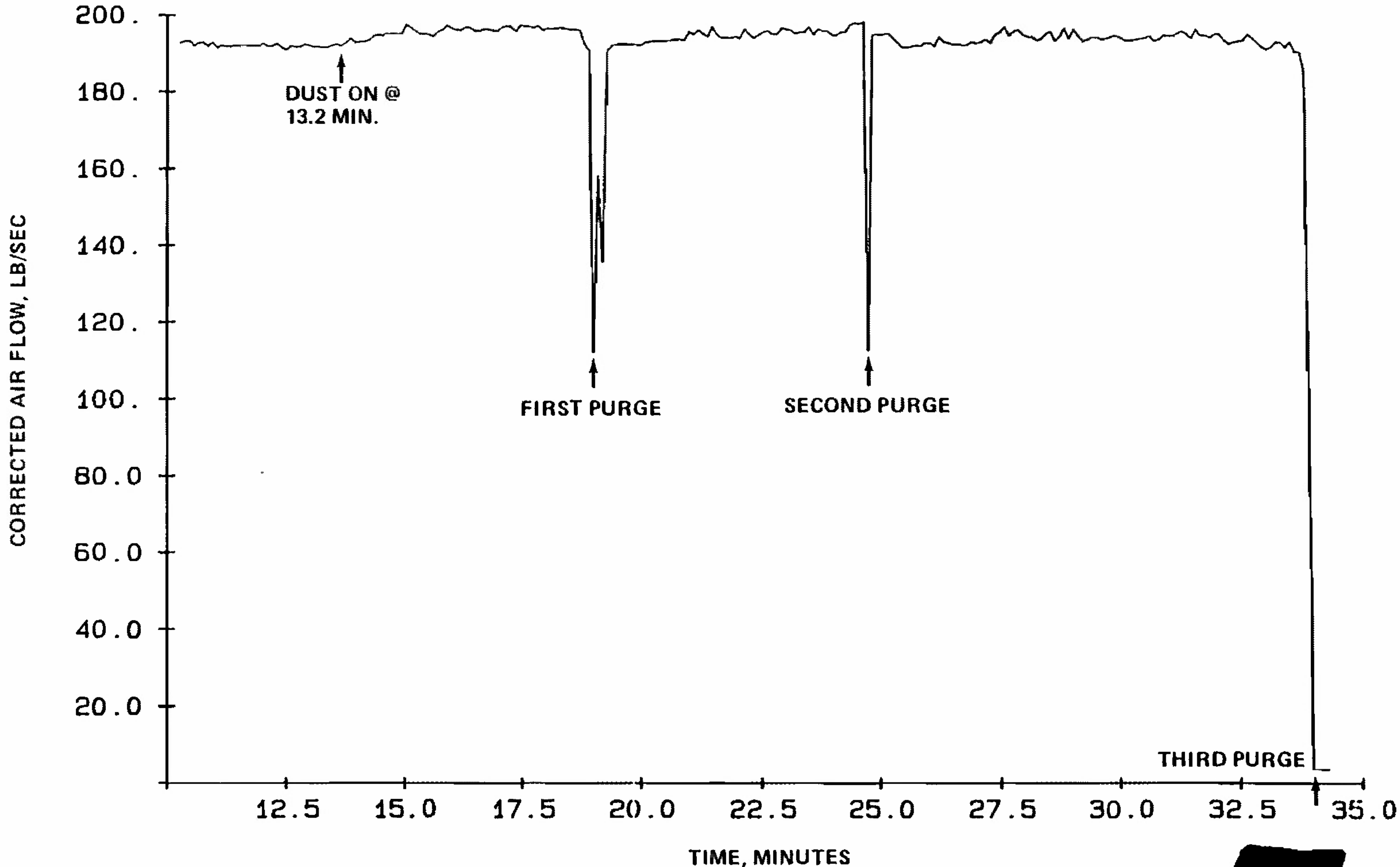


Figure 5. (U) Time history of corrected weight flow of air.

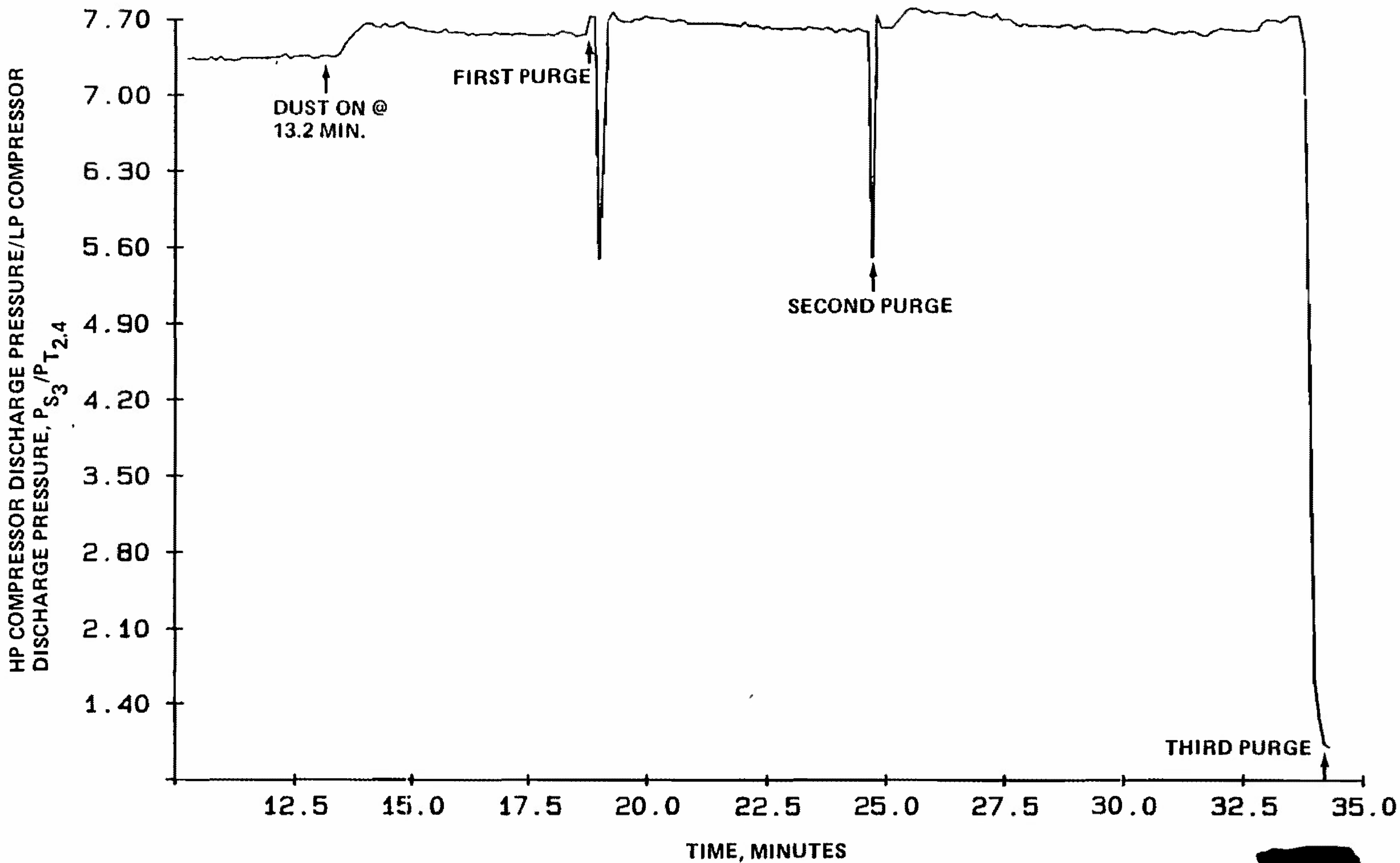


Figure 6. (U) Time history of high-pressure compressor pressure ratio.

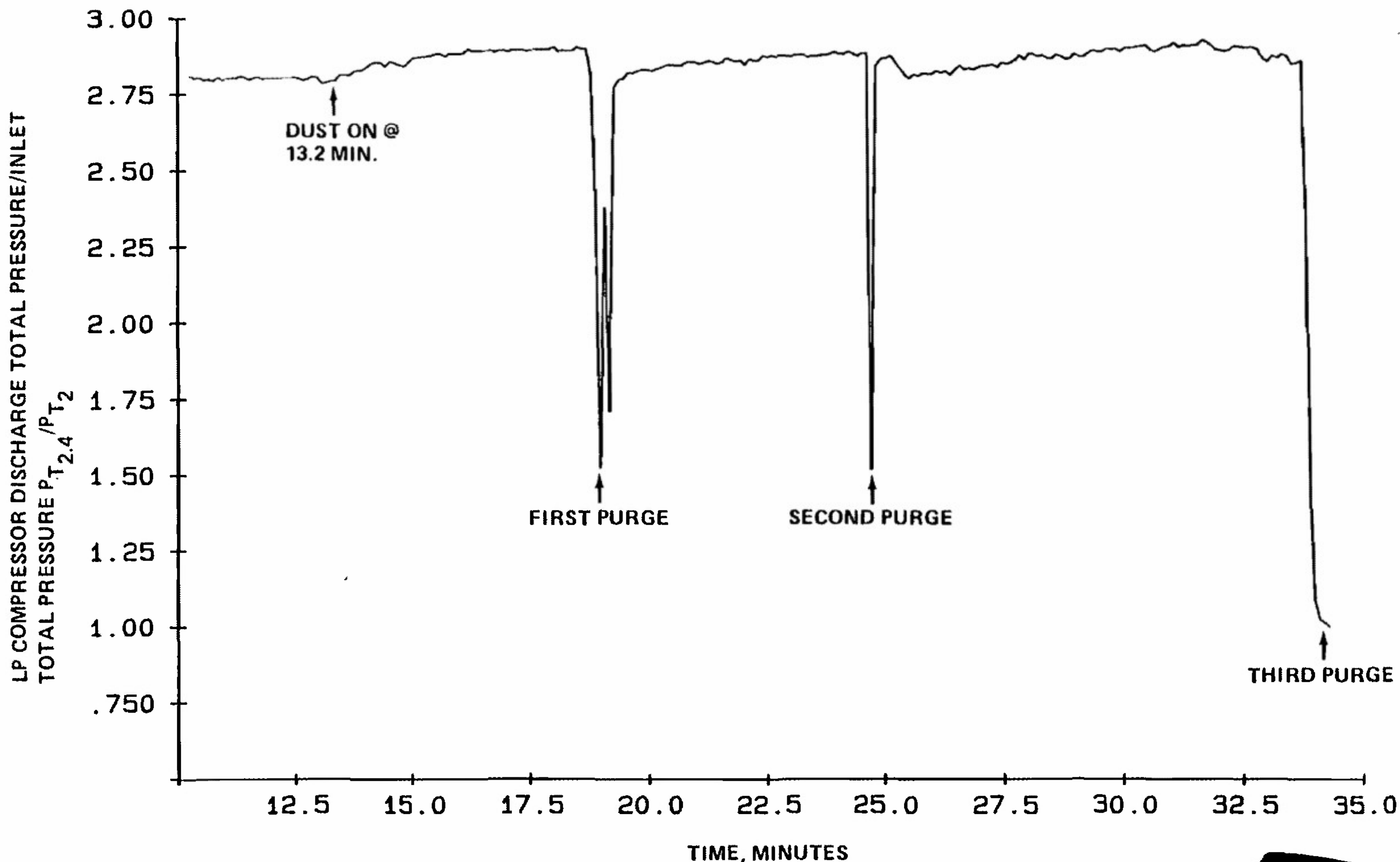


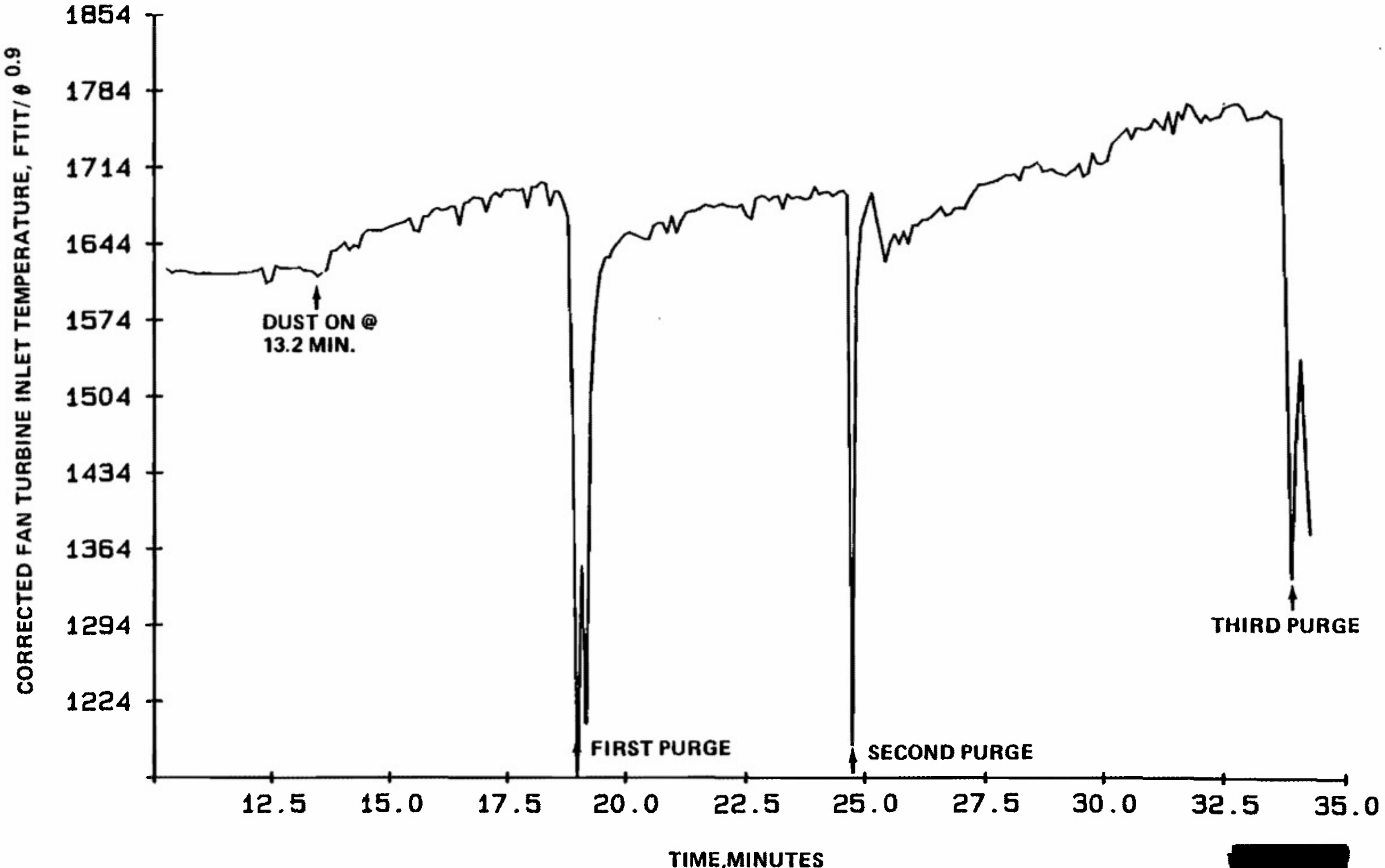
Figure 7. (U) Time history of low-pressure compressor pressure ratio.

about 0.02 per minute until the first purge. After the first purge, the pressure ratio did not return to the pre-dust value but it did return to the peak value that occurred about one-half minute after initiation of the dust flow. Following the second purge, the compression ratio increased to a value higher than the initial peak followed by a steady decline until about thirty-two minutes at which time the trend turned around and the pressure ratio began to increase in a series of steps each about one minute apart. The low-pressure compressor pressure ratio shown in Figure 7 has a different behavior than that just described for the high-pressure compressor. The pressure ratio for the low-pressure compressor increased steadily until the first purge. After the first purge, the pressure ratio returned to near the pre-dust exposure value and then began a steady increase until the second purge. After the second purge, the pressure ratio again returned to the pre-dust exposure value. Near the thirty-two minute point of the third exposure, the pressure ratio began to fall as shown. With the exception of the initial one-half minute of dust exposure, the trend of the low-pressure compressor data during dust exposure was opposite to that of the high-pressure compressor.

[redacted] Figure 8 presents the corrected fan turbine inlet temperature (FTIT) time history. The FTIT responds very quickly to the presence of dust as can be seen from the results presented in Figure 8. The average corrected FTIT increased by 50°F in the first minute of dust exposure. It continued to increase to a peak of nearly 1700°F (up 80°F from the starting value) until just before the first purge. The first purge reduced the corrected FTIT by 60°F. However, after this purge, the FTIT continued to increase by about 6°F per minute. The second purge did little to retard this rate of rise and the FTIT increased at a rate of 14°F per minute for the five minutes following the second purge. Near the end of the third exposure period, the corrected FTIT leveled off at a value near 1760°F as can be seen from Figure 8.

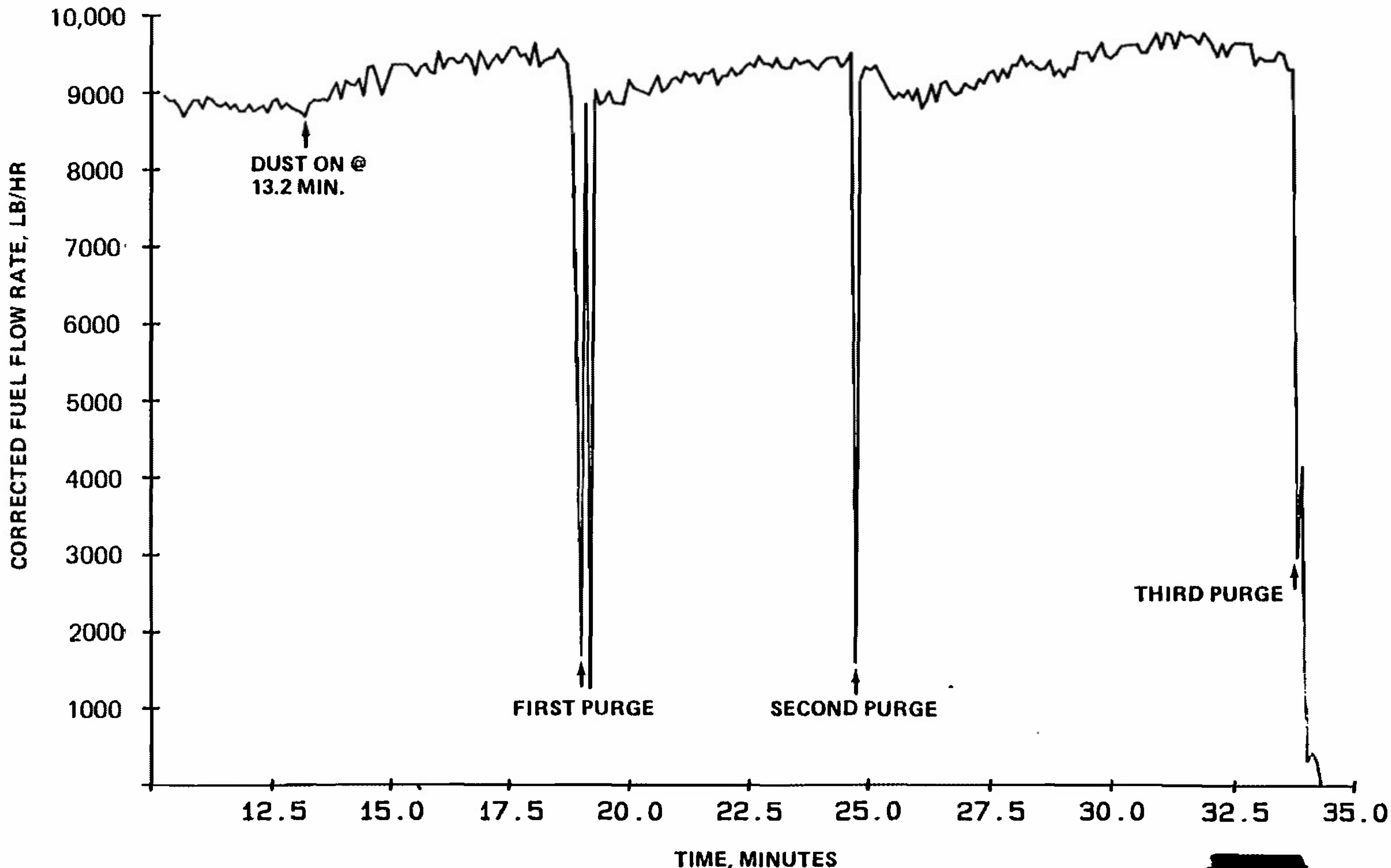
[redacted] Figure 9 presents the time history of corrected fuel flow rate. Very soon after the dust is turned on, the fuel flow rate begins to increase from a pre-dust exposure value in the vicinity of 8800 lbs/hr to a value of about 9500 lbs/hr six minutes later and just before the first purge. Immediately after the first purge, the fuel flow returns to a value that is near the pre-dust exposure value. However, with continued exposure, the flow rate continues to climb at a rate of about 100 lbs/hr for each minute of exposure. After the second purge, the flow rate again returned to the pre-dust exposure value, but once again continued to climb until about two minutes prior to the

[redacted]



[redacted]

Figure 8. (U) Time history of corrected fan turbine inlet temperature.



[redacted]

Figure 9. (U) Time history of corrected fuel flow rate.

third purge at which time the flow rate began to decrease. This decrease is a correction caused by the unified engine control.

[redacted] Figure 10 presents the time history of the fan turbine speed. One of the main functions of the control system is to protect the fan from overspeeding. As soon as the dust is turned on, a gradual increase in fan speed can be observed over the initial six minutes of dust exposure. Immediately after the first purge, the fan speed returned to the pre-dust exposure value. During the second six minutes of dust exposure, the fan speed held very constant. After the second purge, the fan speed again returned to the pre-dust value and remained constant for a very brief period of time. During the third exposure period, the control system became more involved and the fan speed decreased from the pre-dust value slowly from about 26 minutes until about 32 minutes, but then decreased in stepwise fashion over the final 2.5 to 3 minutes.

3.5 (U) Test series terminating event.

[redacted] The preceding section has demonstrated that we attempted rapid accelerations and decelerations as a way to clear the deposited material from the hot section. On two occasions, this technique worked very well. However, on the third attempt, the engine began to surge uncontrollably at a rate of 12 surges per second. This surging was accompanied by a significant tail pipe fire and it was necessary to terminate the fuel flow to the engine in order to regain control and to put out the fire. The engine was motored using the air start cart in order to finally extinguish the fire and cool the engine. During the test series there were three video cameras photographing the engine. One video camera was focused on the tail pipe, a second one on the front face of the engine, and the third on the side of the engine. Several photographs of selected frames from these videotapes were made and are presented in the following paragraphs.

[redacted] Figure 11 is a photograph of the tailpipe taken during one of the surges that illustrates that the tailpipe was completely engulfed in fire. The time at the lower left hand corner of the photograph is the time of day and can be used to orient the events. However, it should be noted that the camera films at sixty frames/sec and the least count on the timer is one second. Therefore, one might see the same time on two photographs, but the photographs would be of different events. Figure 12 was taken between two successive surges so that the details of the flowfield are not

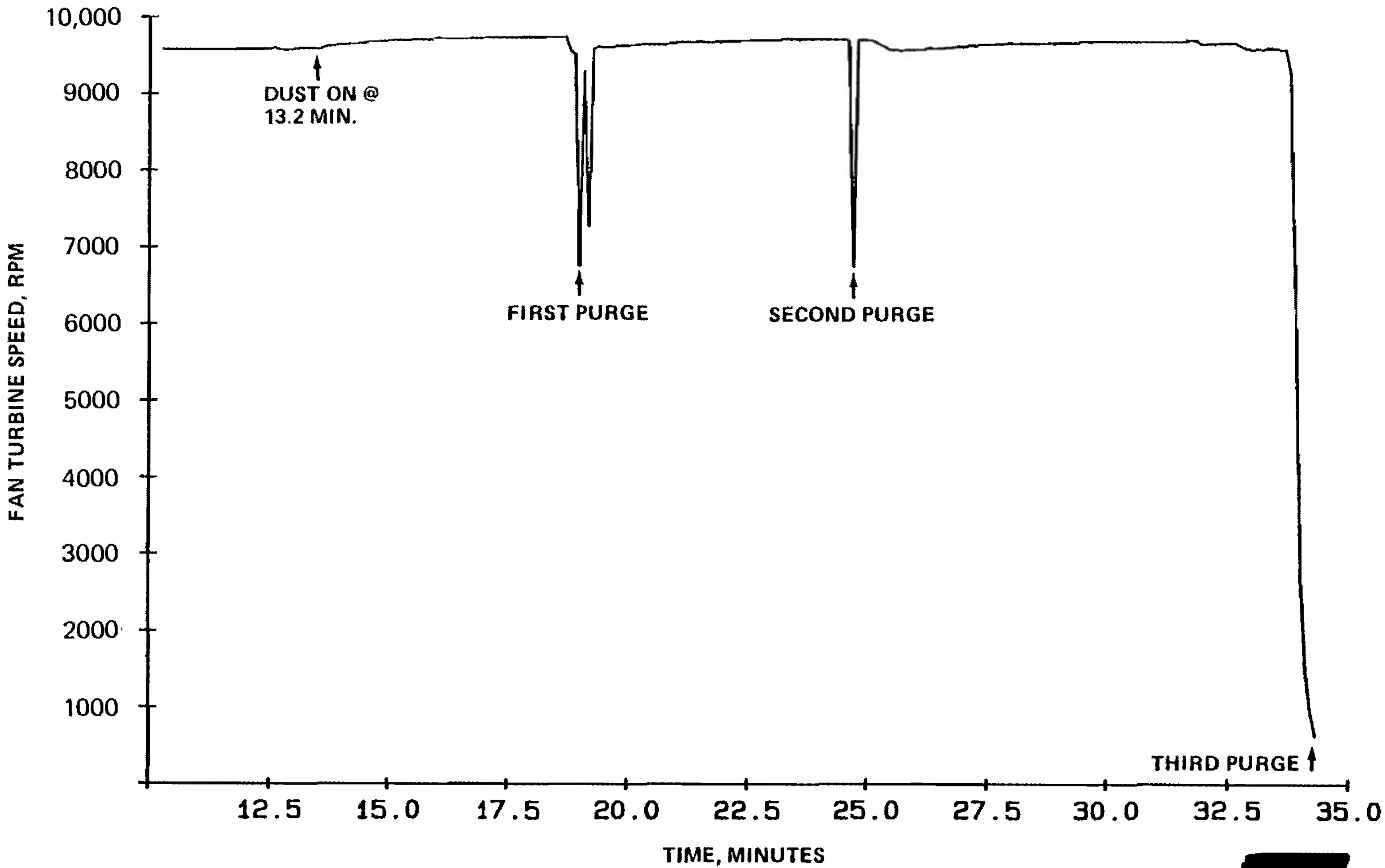
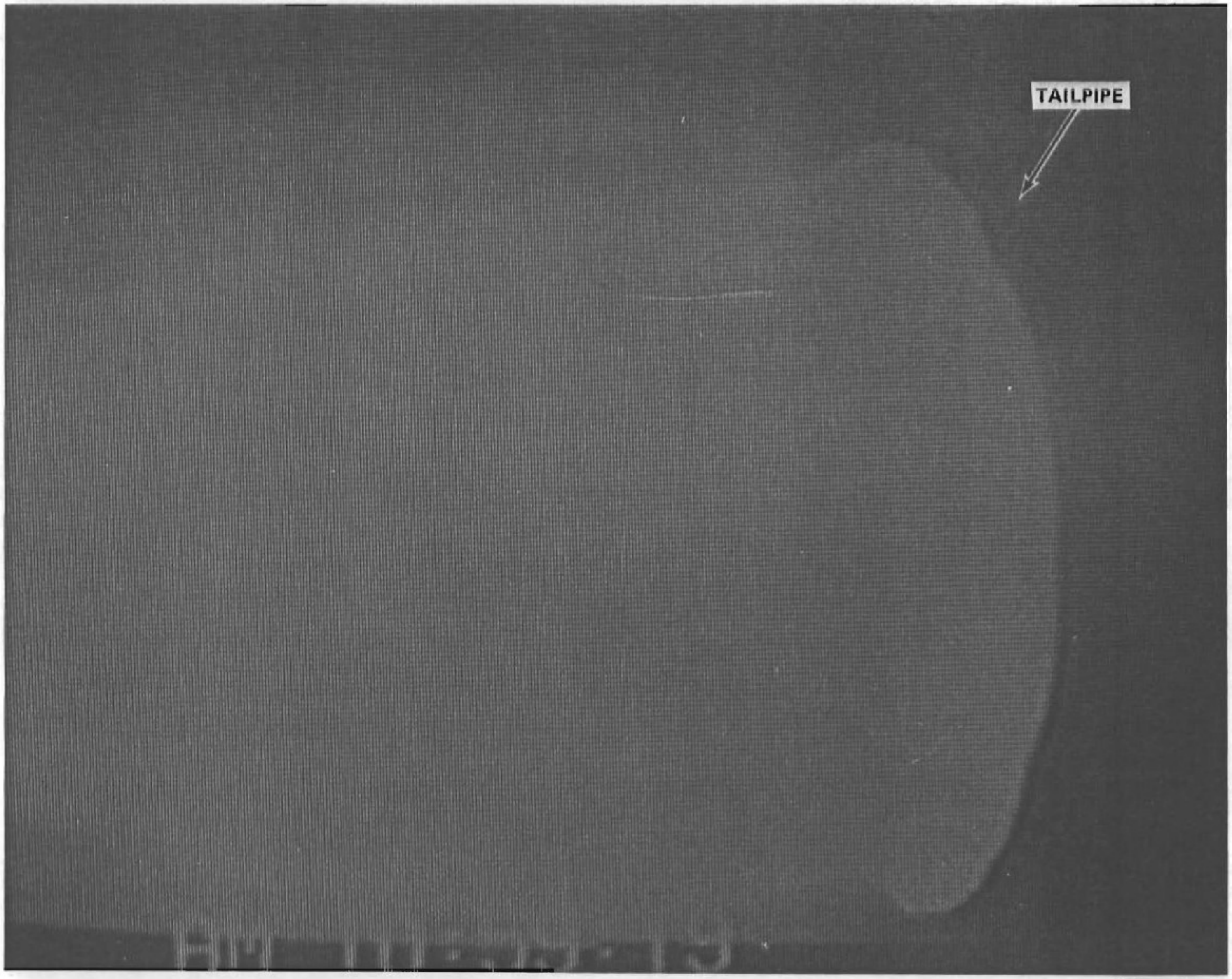


Figure 10. (U) Time history of fan turbine speed.

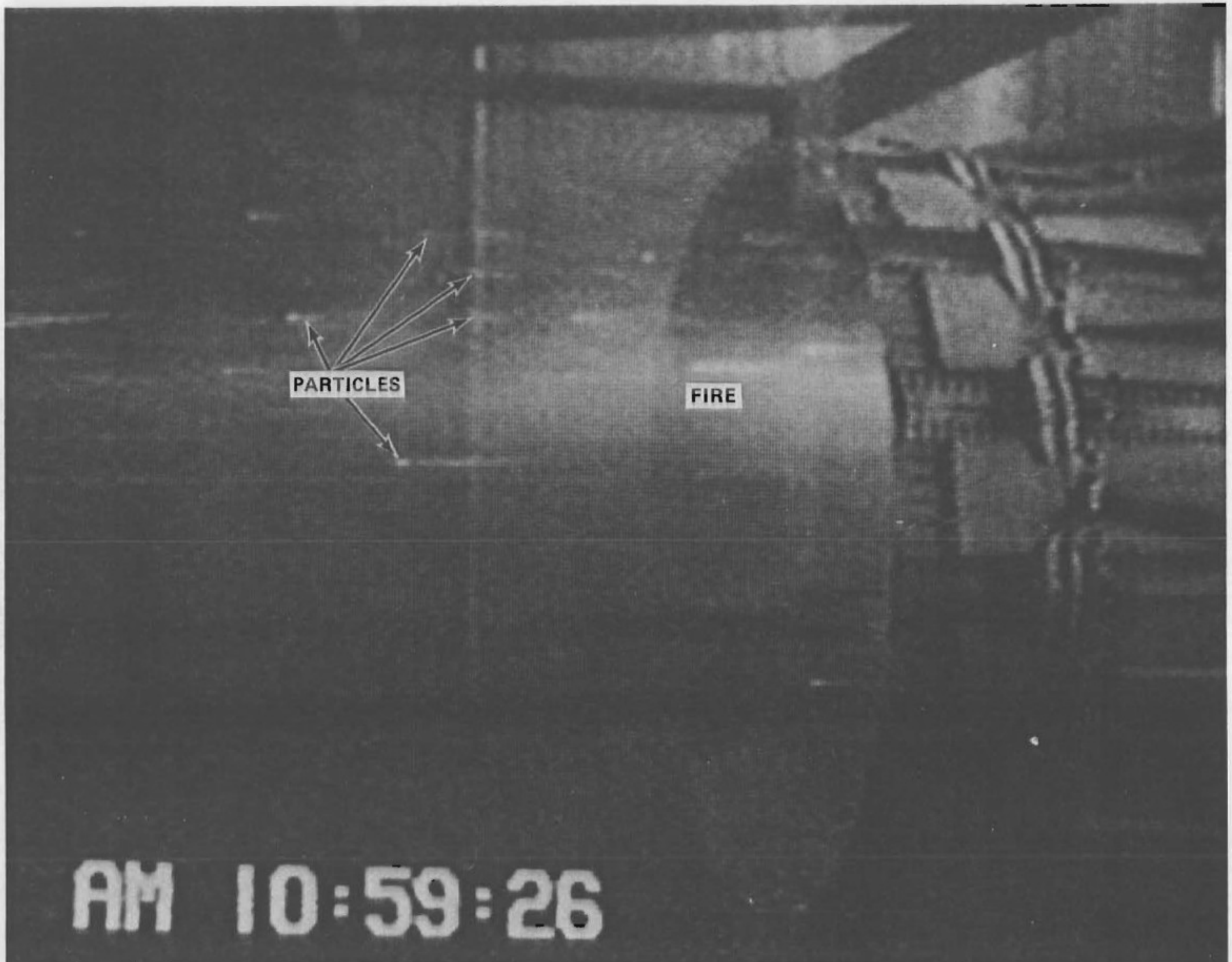


[redacted]

[redacted]

Figure 11. (U) Photograph of tailpipe surge.

[redacted]



[redacted]

Figure 12. (U) Photograph of particles exiting machine during surge event.

[redacted]

obliterated by the brightness of the flame. On this photograph, one can easily see a few glowing particles exiting the tailpipe of the engine. Figure 13 is a third photograph taken during the surge events that again illustrates many glowing particles and a reduced amount of flame exiting the tailpipe. After inspection of the engine components during the teardown, it is felt that the glowing particles seen in these photographs are pieces of the glassified material that have been purged from the hot section of the machine and they are probably not pieces of metal removed from the machine.

[redacted] Figure 14 is a side-view photograph of the engine taken during the surge event. The viewer gets a good view of the extent of the flame in the tailpipe region from this photograph. The entire backwall of the test cell is illumianted by the flame. Figure 15(a) is a front view photograph taken prior to the start of the throttle excursion at a time of 10:56:26. Therefore, this photograph was taken a little less than three minutes prior to the event that resulted in violent surging of the engine. The St. Elmo's glow at the fan face is clearly visible. The glow is the result of a static discharge caused by the dust particles flowing into the engine being struck by the rotating fan blades. The dark region in the center of the photograph is the nose cover which is stationary. Figure 15(b) is a photograph taken with the same camera at a time of 10:59:19 which was during throttle excursion. This photograph was taken immediately before a surge. Note that the St. Elmo's glow has disappeared, suggesting that axial flow of air through the machine has stopped. Figure 16 is a photograph taken during the surge event. The time on the photograph is also 10:59:19 but as noted earlier, the camera records sixty frames/sec and the clock only updates on a one-second basis. The photograph illustrates a bright ring of light around the fan perimeter which is a view of the fire propagating forward. To confirm that the fire did propagate forward, after the engine was shut down a very bright light was placed at the exit of the low-pressure turbine. No light could be seen at the fan face.

[redacted] It was noted earlier in this section that the surging was finally stopped and the engine was brought under control by terminating the fuel flow. After allowing the engine to cool for several hours, many unsuccessful attempts were made to restart. Since it was not possible to operate the engine any longer, the decision was made to remove it from the test cell and ship it to Kelly AFB for disassembly.

Figure 13. (U) Photograph of particles and flame exiting tailpipe during surge event.

[redacted]

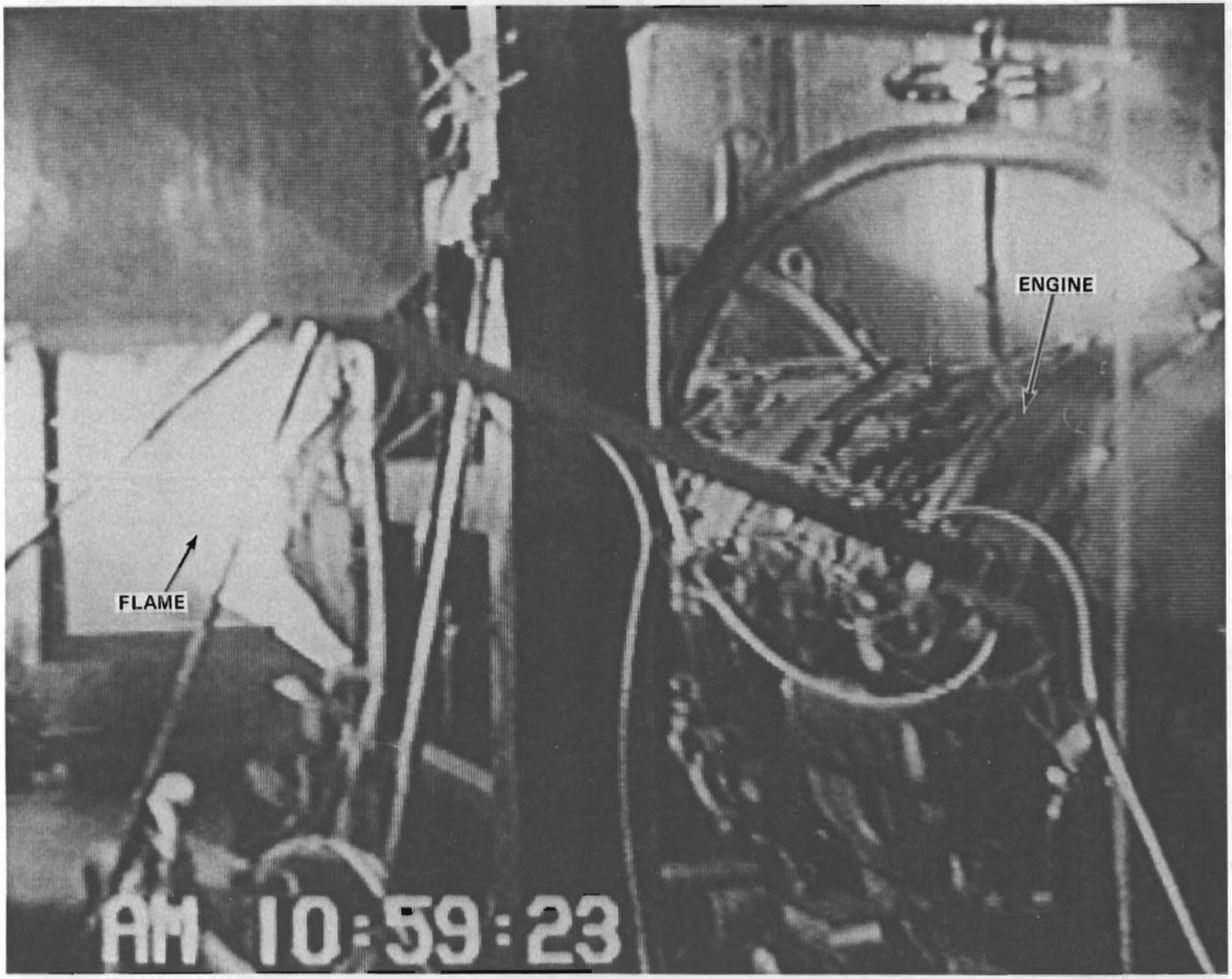


Figure 14. (U) Side view photograph of engine during surge event.

[redacted]

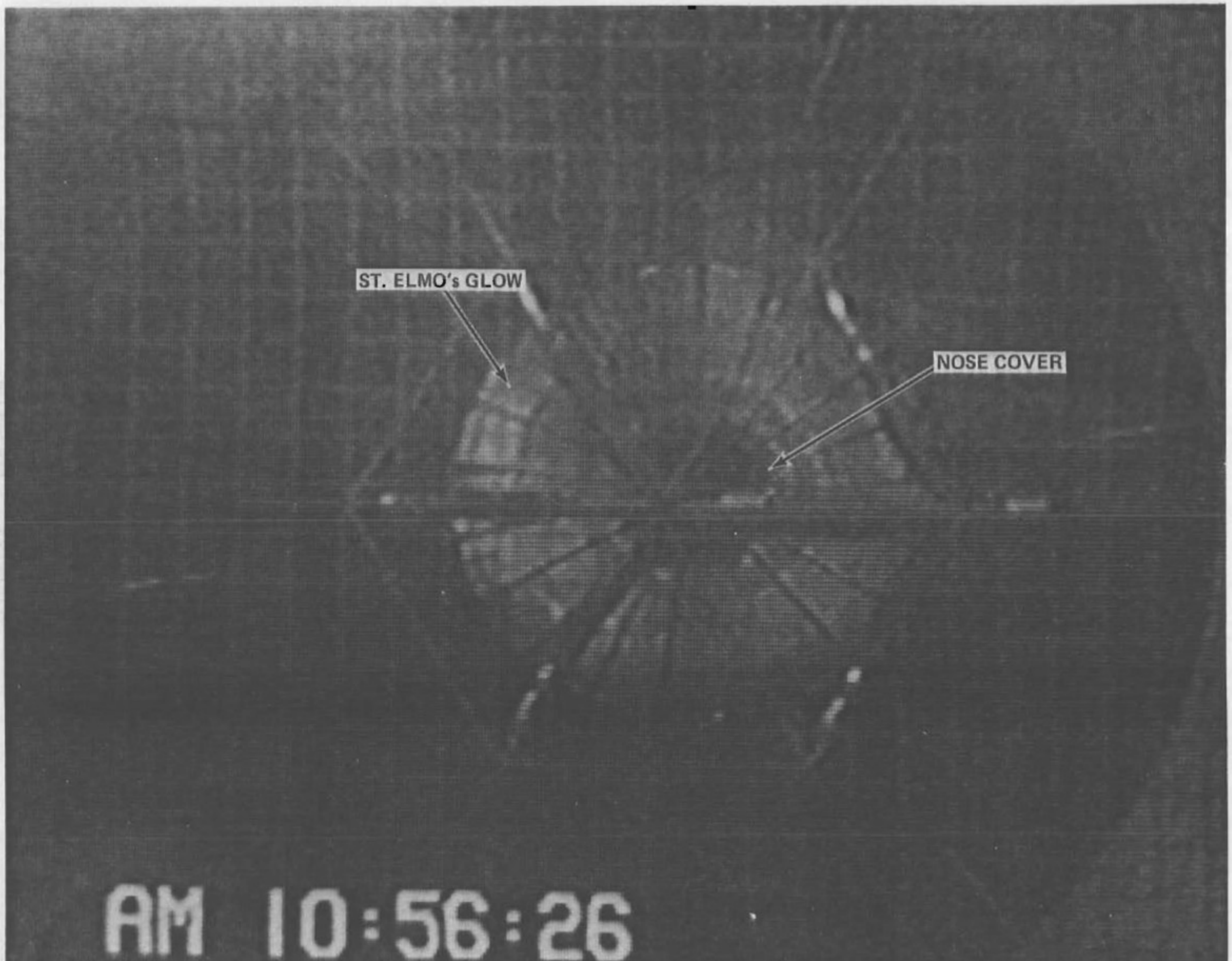


Figure 15a. (U) Front view photograph of engine taken prior to throttle excursion. [redacted]

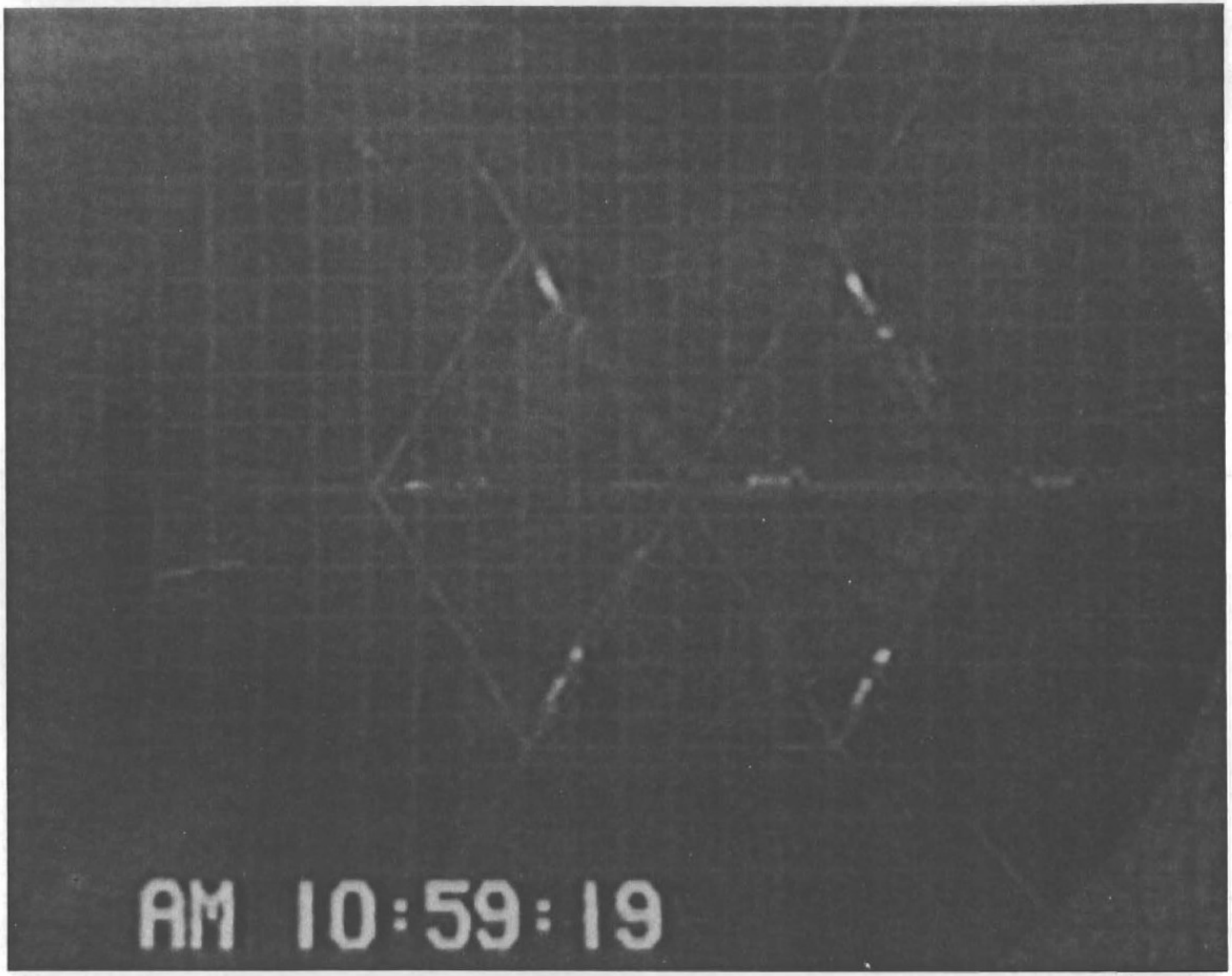


Figure 15b. (U) Front view photograph of engine taken during throttle excursion and just prior to surge event.

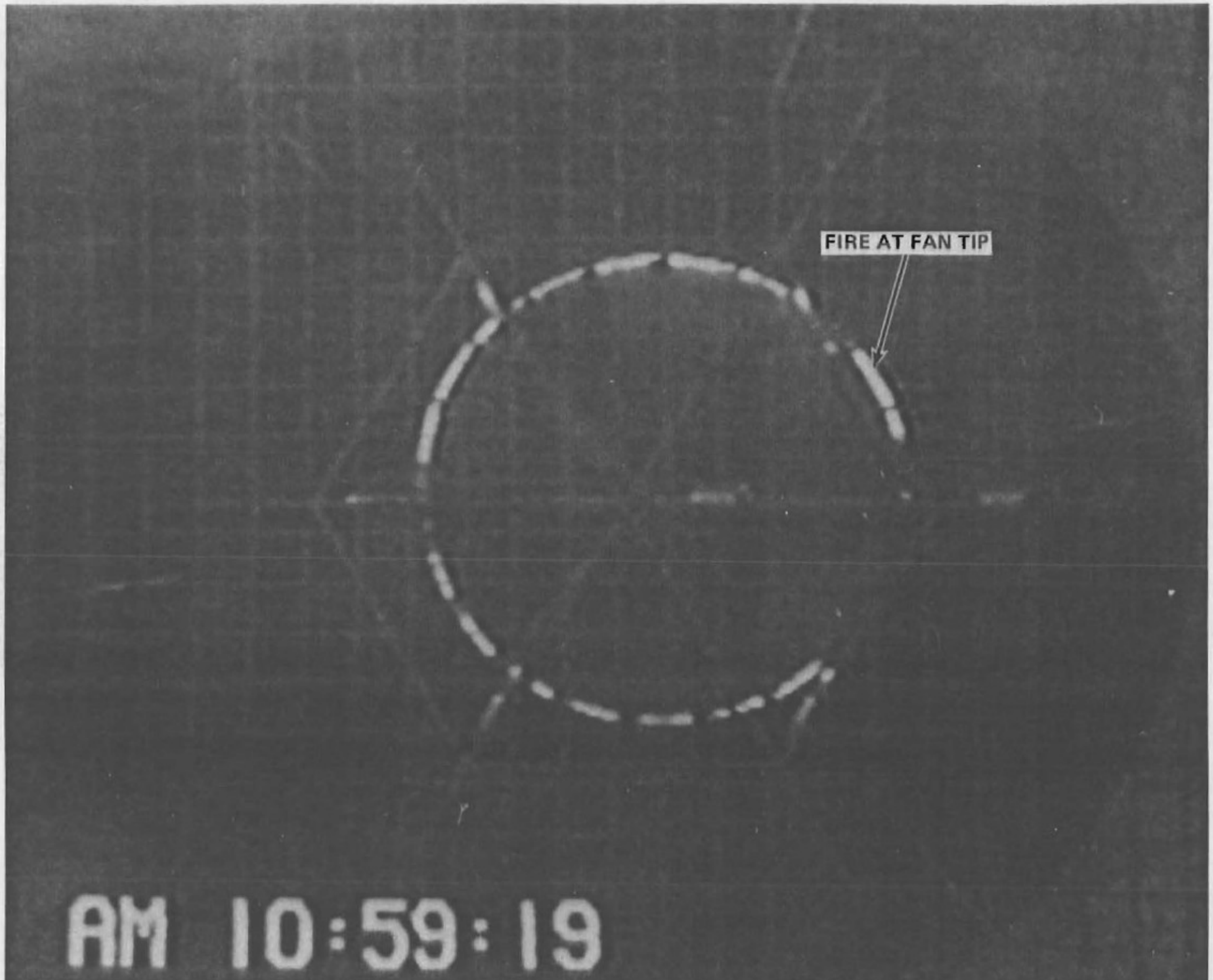


Figure 16. (U) Front view photograph of engine taken during surge event.

3.6 (U) Discussion of teardown of engine S/N P680054.

(U) The F100-100 engine used in this test program (S/N P680054) was completely disassembled at Kelly AFB during the period 4 to 11 January 1990. Detailed photographic coverage of the disassembly was provided by Kelly and the results will be illustrated in this section. After removal of accessory equipment, the engine is taken apart starting at the afterburner and progressing forward. It was at this point in the disassembly process that fuel and oil samples were taken for laboratory analysis. Table 3 gives the results of the fuel analysis and indicates that the contaminant in the fuel was far less than the allowable limit. Table 4 presents the results of the laboratory analysis for oil samples taken from six different locations. The iron and silicon levels were high but they were within allowable limits for all locations. The highest contamination level was found in the filter region. The maximum allowable levels of iron and silicon for field operation are 10 ppm and 15 ppm, respectively.

Table 3. (U) Results of teardown fuel analysis.

Sample	Particulate Matter*
F100 engine, S/N P680054	0.8 mg/gallon

*limit is 4.0 mg/gallon maximum according to T.O. 428-1-1.

(UNCLASSIFIED)

Table 4. (U) Results of teardown oil analysis F100 engine, S/N P680054.

Location	Fe	Ag	AL	Cr	Cu	Mg	Ni	Si	Ti
#1 Bearing	3	0	0	0	0	1	1	6	2
#2 & #3 Bearing	4	0	0	0	0	1	1	7	2
#4 bearing	3	0	0	0	0	2	0	6	2
#5 bearing	3	0	0	0	0	1	1	6	1
Filter	5	0	0	0	0	2	1	11	2
Tank	5	0	0	0	1	2	1	9	2

The allowable limits are: Fe = 10 Ag = 2 Al = 10 Cr = 4
Cu = 3 Mg = 8 Ni = 4 Si = 15 Ti = 20

(UNCLASSIFIED)

[redacted] Our discussion of the teardown will progress in the manner in which the engine is taken apart, starting with the tailpipe and working towards the fan. There was a large amount of loose material laying in the tailpipe. This material had the same appearance as the material collected from the combustor, photographs of which will be shown in Section 3.6.1. Some of the tailpipe material was collected for later analysis. Except for this material, there was nothing of interest in the tailpipe.

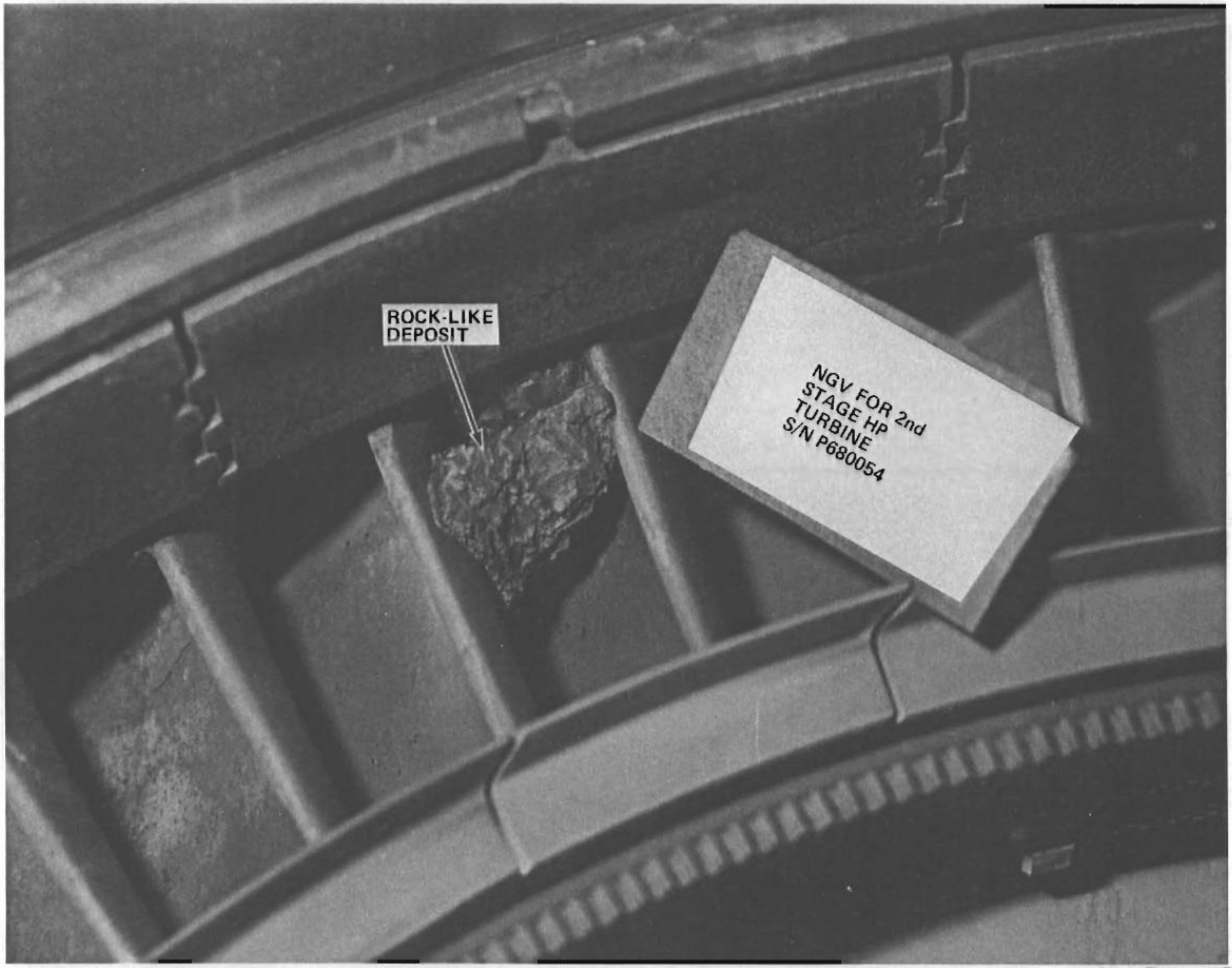
3.6.1 (U) Hot section of machine.

[redacted] None of the low-pressure turbine (LPT) stages showed anything unusual. The brownish discoloration was the same as seen on the previous F100 engine. There were neither deposits on nor erosion of the LPT components. Nothing of any significance was seen until the teardown reached the nozzle guide vane row for the second stage of the high pressure turbine. Figures 17 and 18 are photographs of material found in this vane row. Figure 17 shows one of these pieces of material which was found to be very hard (rock-like) and blocked about 40% of the particular flow passage. Figure 18 is another photograph taken of the NGV for second stage high-pressure turbine showing two other deposits. These deposits were also very hard. Neither of them blocked as large a portion of the passage as did the deposit shown in the previous photograph, but perhaps that is because the deposits appear from the photograph to have fractured. Several very hard pieces similar to those shown in Figures 17 and 18 were found in the combustor liner, the implication of this is that they were blown forward in the engine during the multiple surge event described in Section 3.5.

[redacted] Figure 19 is a photograph of the first-stage high-pressure turbine rotor. There was a light deposit of material on the pressure surface and a little heavier deposit on the pressure surface near the hub. However, this material was not of a glassy nature and could be removed with relative ease.

[redacted] Figures 20, 21 and 22 are photographs taken of different portions of the high-pressure turbine first stage nozzle guide vane. Figure 20 illustrates the large deposit completely covering the vane leading edge. The cooling holes near the inner hub appear to still be open. However, beyond midspan the holes are blocked. Very heavy deposits on the vane pressure surface can be seen on two of the vanes shown in this photogrpah. One of the vanes is free of deposits, but the flakes remaining on the

[redacted]



[redacted]

Figure 17. (U) Photograph of nozzle guide vane for second stage high-pressure turbine.

[redacted]

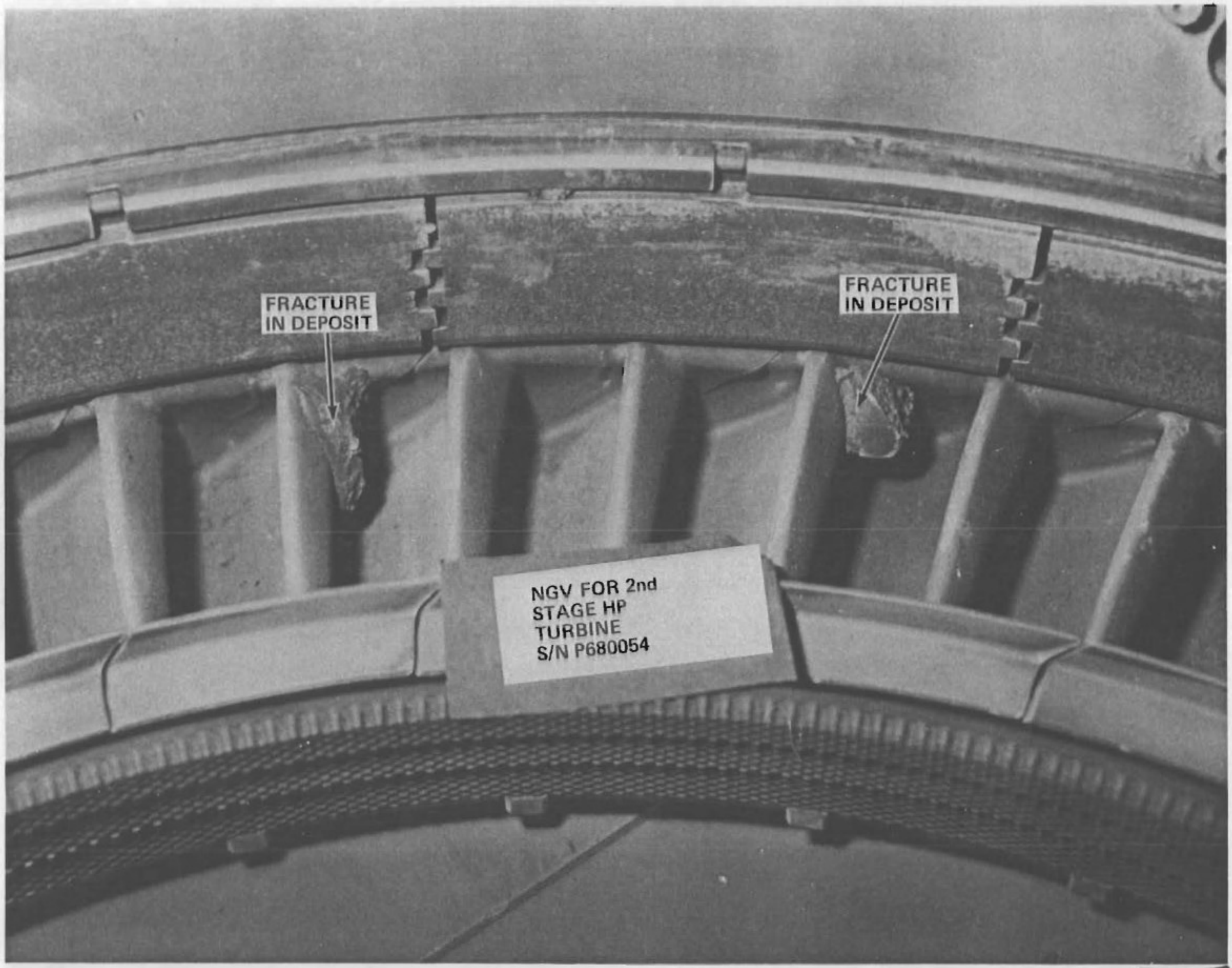


Figure 18. (U) Photograph of nozzle guide vane for second stage high-pressure turbine.

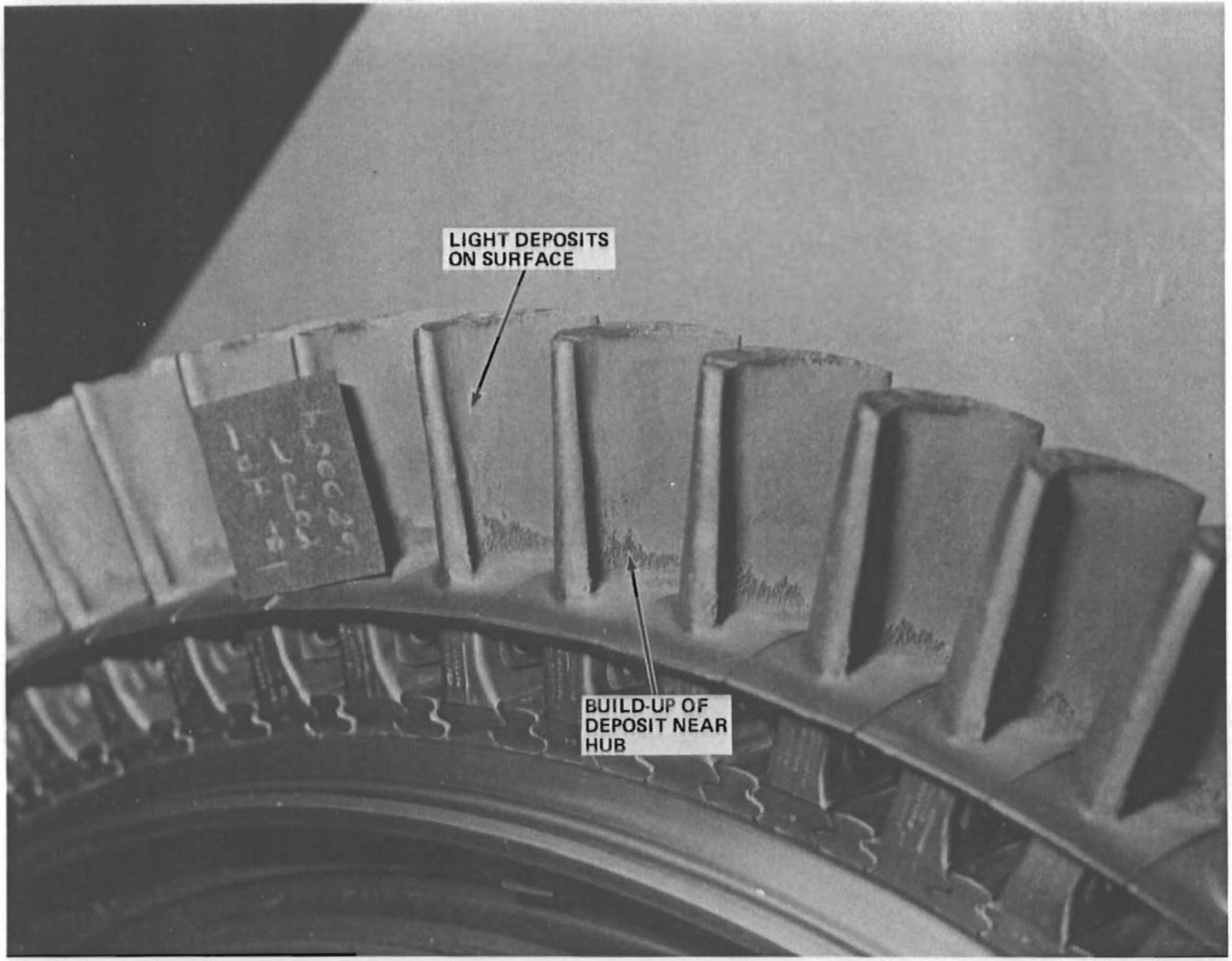


Figure 19. (U) Photograph of first-stage high-pressure turbine rotor.

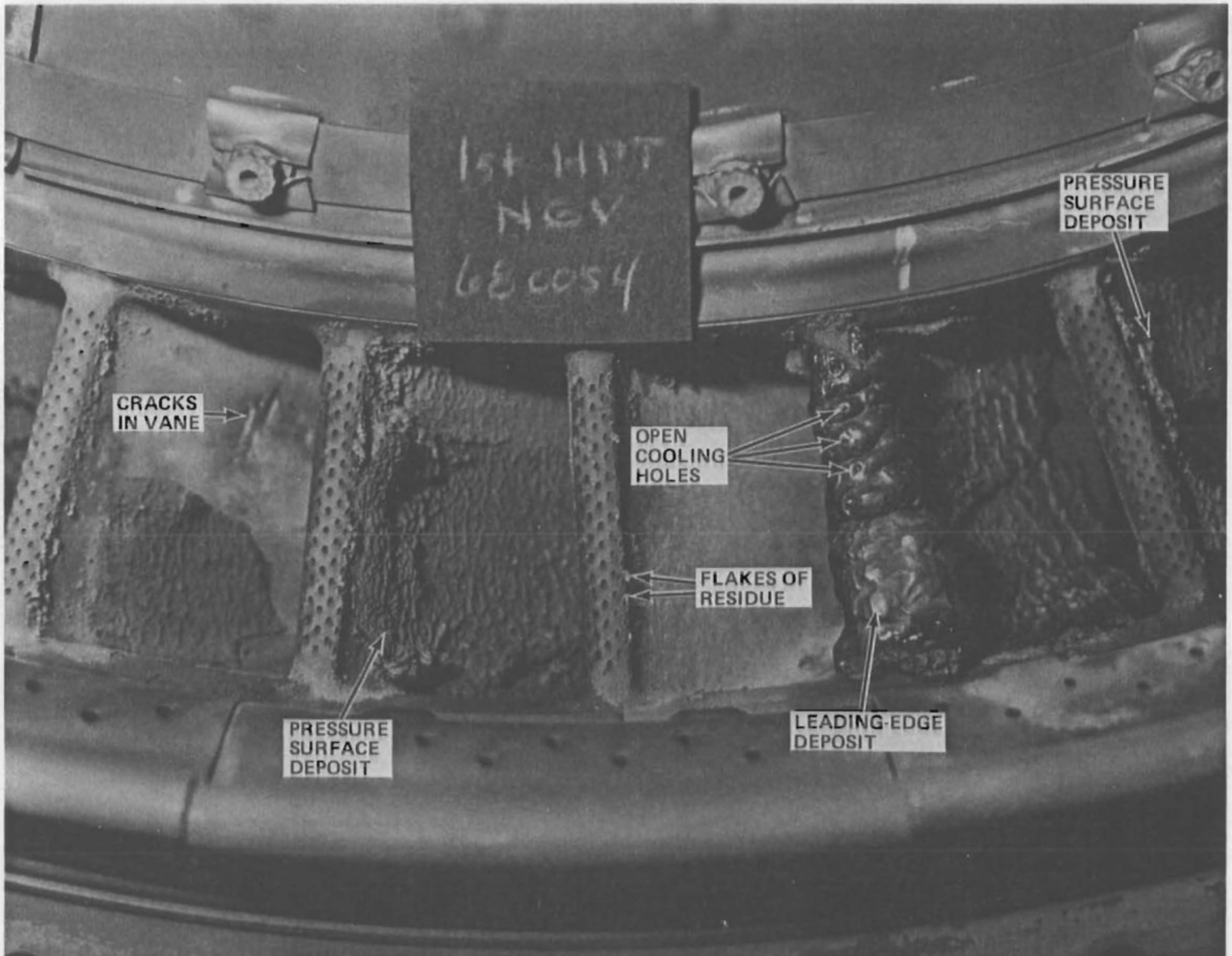


Figure 20. (U) Photograph of nozzle guide vane for first stage high-pressure turbine.

[redacted]

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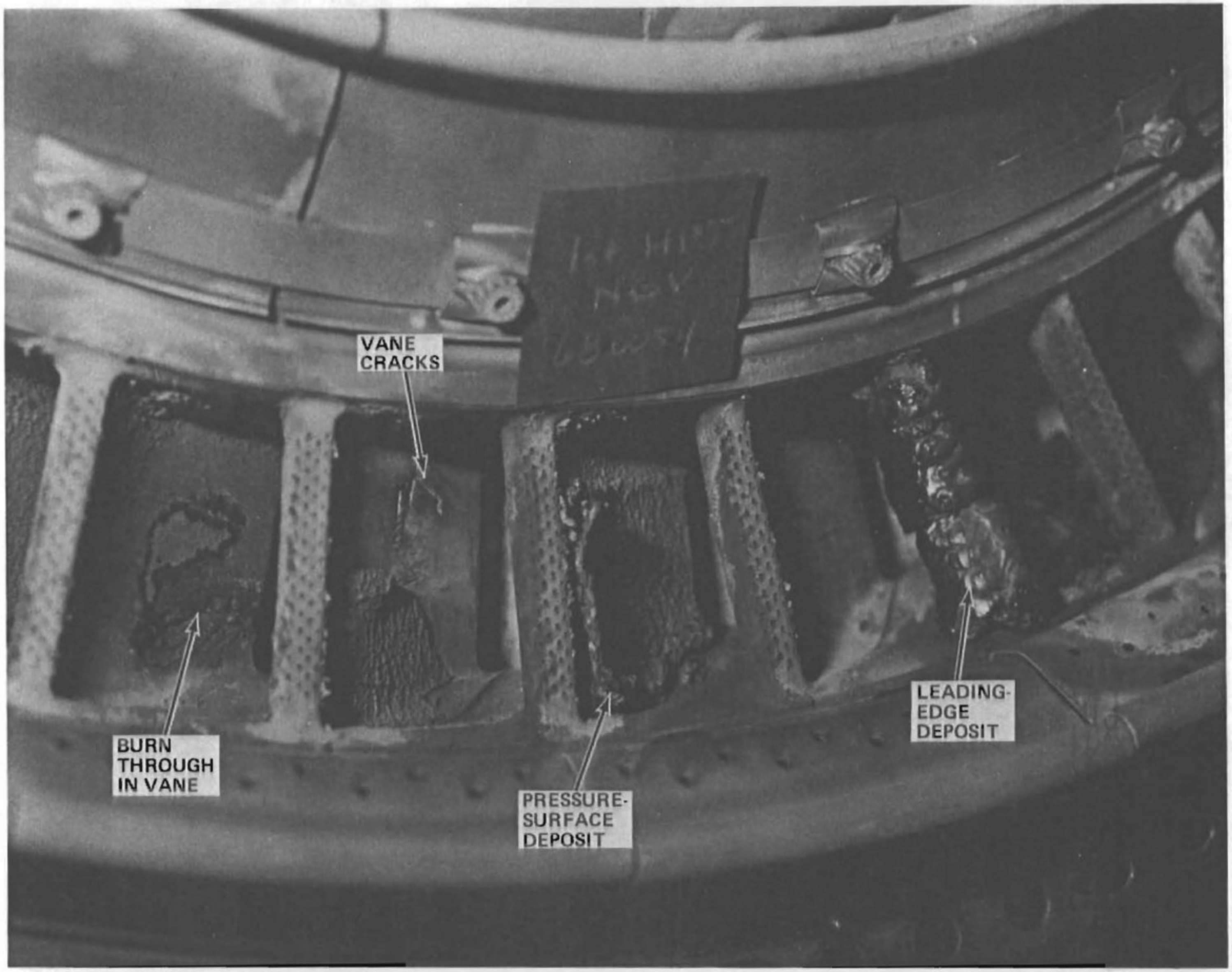

Figure 21. (U) Photograph of nozzle guide vane for first stage high-pressure turbine. [redacted]

[redacted]

[redacted]

[redacted]

Figure 22. (U) Photograph of nozzle guide vane for first stage high-pressure turbine.

[redacted]

surface suggest that there was a deposit there, but it had been blown away. The vane to the far left of the photograph is one for which the leading edge deposit and a portion of the pressure surface deposit have been blown away. A large quantity of this deposit that we claim has been blown away was recovered from the combustor liner. Photographs of the material taken from the combustor liner will be shown later to demonstrate that they, in fact, came from the guide vane shown in Figures 20 to 22.

[redacted] Figure 21 is a photograph of a different portion of the nozzle guide vane of the first stage high-pressure turbine. The vane to the far left has been burned through the pressure surface to the suction surface. The vane next to this one had some large cracks, but didn't appear to burn through. The vane in the center has a large deposit on the pressure surface, but the leading-edge deposit has blown away. Note that the deposit does not adhere well to the vane surface after the component cools and that this is consistent with the result reported in Reference 2. The vane on the right side of Figure 21 has a heavy deposit on the leading edge and on the pressure surface. This is the same deposit shown in the close-up view of Figure 20 and was described in conjunction with that photograph. Figure 22 is a close-up photograph of another of the leading-edge deposits on the vane. It appears that this deposit has blocked all of the cooling holes. The deposit further along the pressure surface of this vane has blown away.

[redacted] Figure 23 is a photograph taken looking down into the combustor liner. It was difficult to get a photograph of the inside of this liner, but visually one could see many glassy deposits attached to the liner. At the bottom of the liner near the location where the fuel nozzles are located, many bead-like glassy deposits could be seen. Looking down into the liner, a lot of black sooty-like material could be seen also attached to the liner sidewall. The material shown lying in the bottom of the liner was loose and fell out as soon as the liner was tipped on end.

[redacted] Figure 24 is a photograph of a portion of this loose material that fell out of the combustor liner at disassembly. Many of the pieces shown in this photograph can be identified as having come from the vane leading edge, the vane pressure surface, and the combustor liner wall. Figure 25 is a close-up photograph of several of these pieces that came from the vane leading edge. When these pieces were held up to the

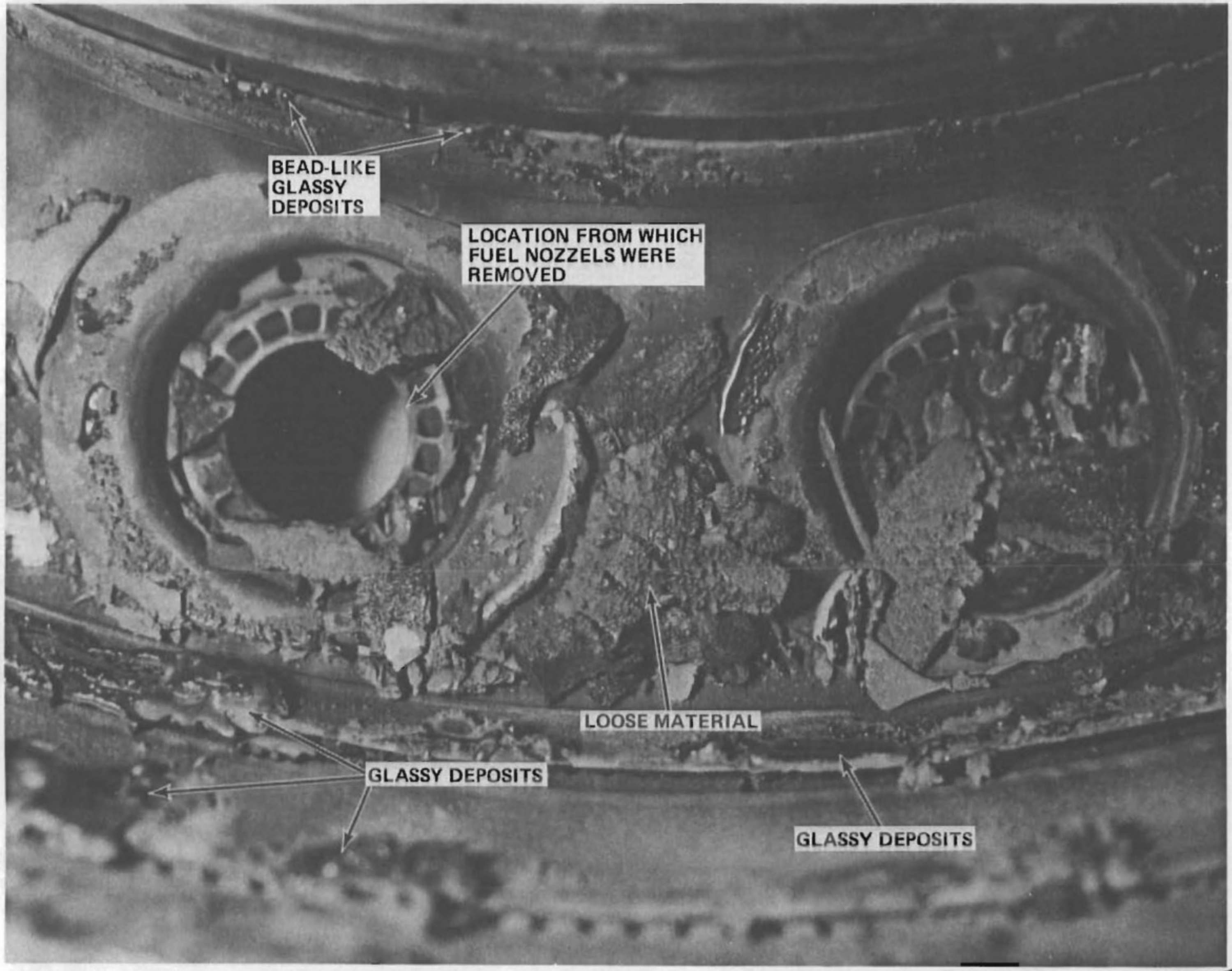

Figure 23. (U) Photograph of combustor liner.

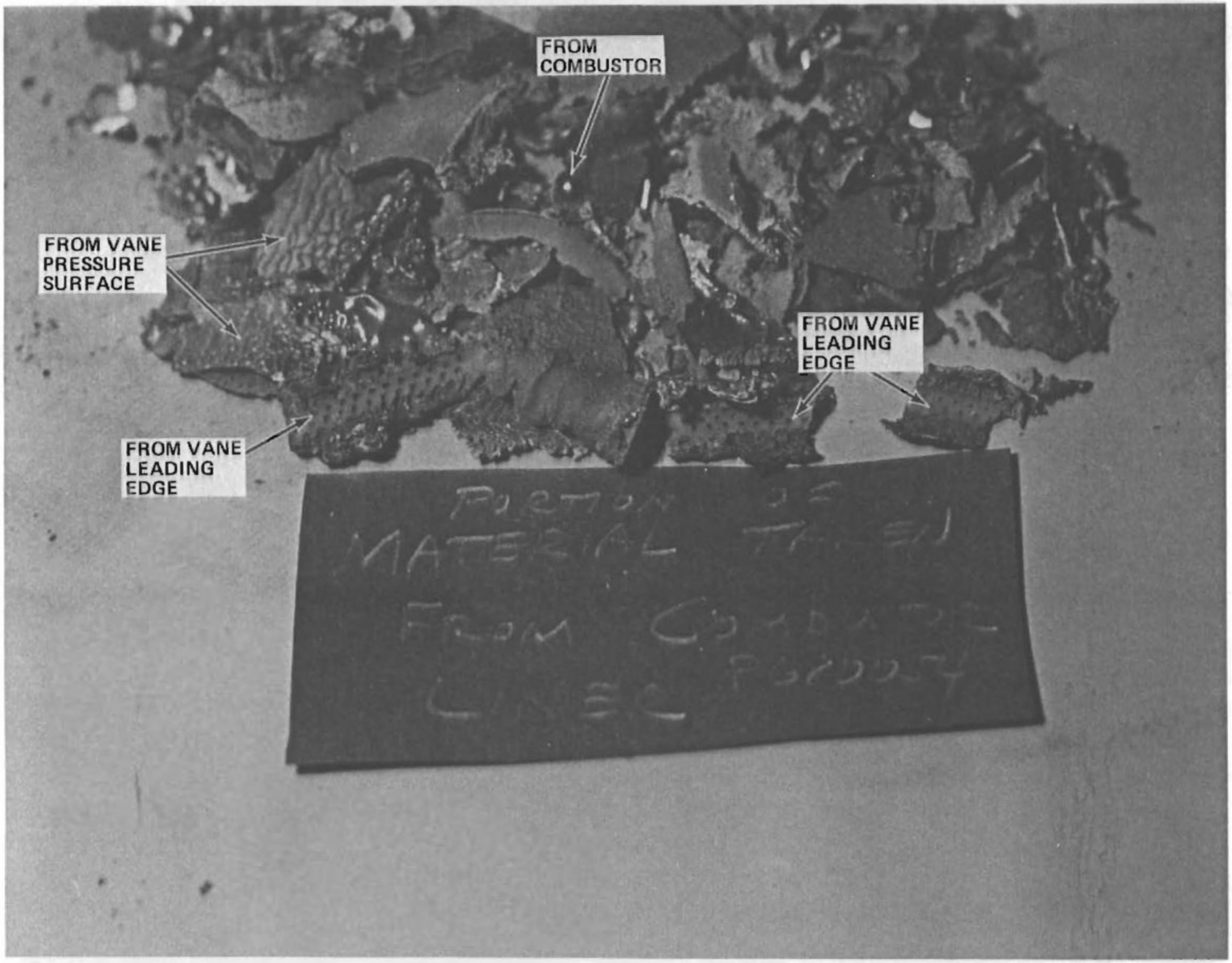

Figure 24. (U) Photograph of material that fell out of combustor liner.

Figure 25. (U) Close-up photograph of pieces that came from NGV leading edge.

light, some of the cooling holes were open and air could have flowed through them, but many others were blocked. The piece of material on the left appears to have taken a portion of the pressure surface deposit with it when it was blown away from the surface. On the other two pieces, the portion of the deposit towards the bottom of the picture probably came from the suction side and appears to have been hotter than the other material.

[redacted] The heavy deposits on the nozzle guide vane of the first stage of the high-pressure turbine are felt to have caused the rapidly increasing burner pressure and compressor discharge pressure that were illustrated in Section 3.4. These deposits caused excessive blockage at the NGV causing the operating line to move dangerously close to the surge line. In attempting to clear the deposits on the third purge attempt, the capability of the machine to operate normally was exceeded and the uncontrollable surge described in Section 3.5 resulted.

[redacted] Figure 26 is a close-up photograph of three of the fuel nozzles taken out of the combustor. The center hole of the nozzle is open so that fuel could be sprayed into the combustor, but the swirl vanes are badly blocked. Without air passing through these swirl vanes, fuel atomization in the combustor would not be as good as it should be. The condition of the fuel nozzles is felt to be a significant contributor to the reason why we could not start the engine after the surge event described in Section 3.5

[redacted] All of the significant damage to the second F100 engine occurred in the hot section. The first F100 engine had relatively minor damage to the hot section but major damage to the compressor. The following section of this report is devoted to a discussion of the compressor component of the machine.

3.6.2 (U) Compression section of machine.

[redacted] The tip clearance was measured as the compressor section of the machine was taken apart. Table 5 presents a stage by stage comparison between the measured tip clearances at disassembly and the maximum and minimum allowable values. The only two stages that are significantly outside of allowable maximum values are stages

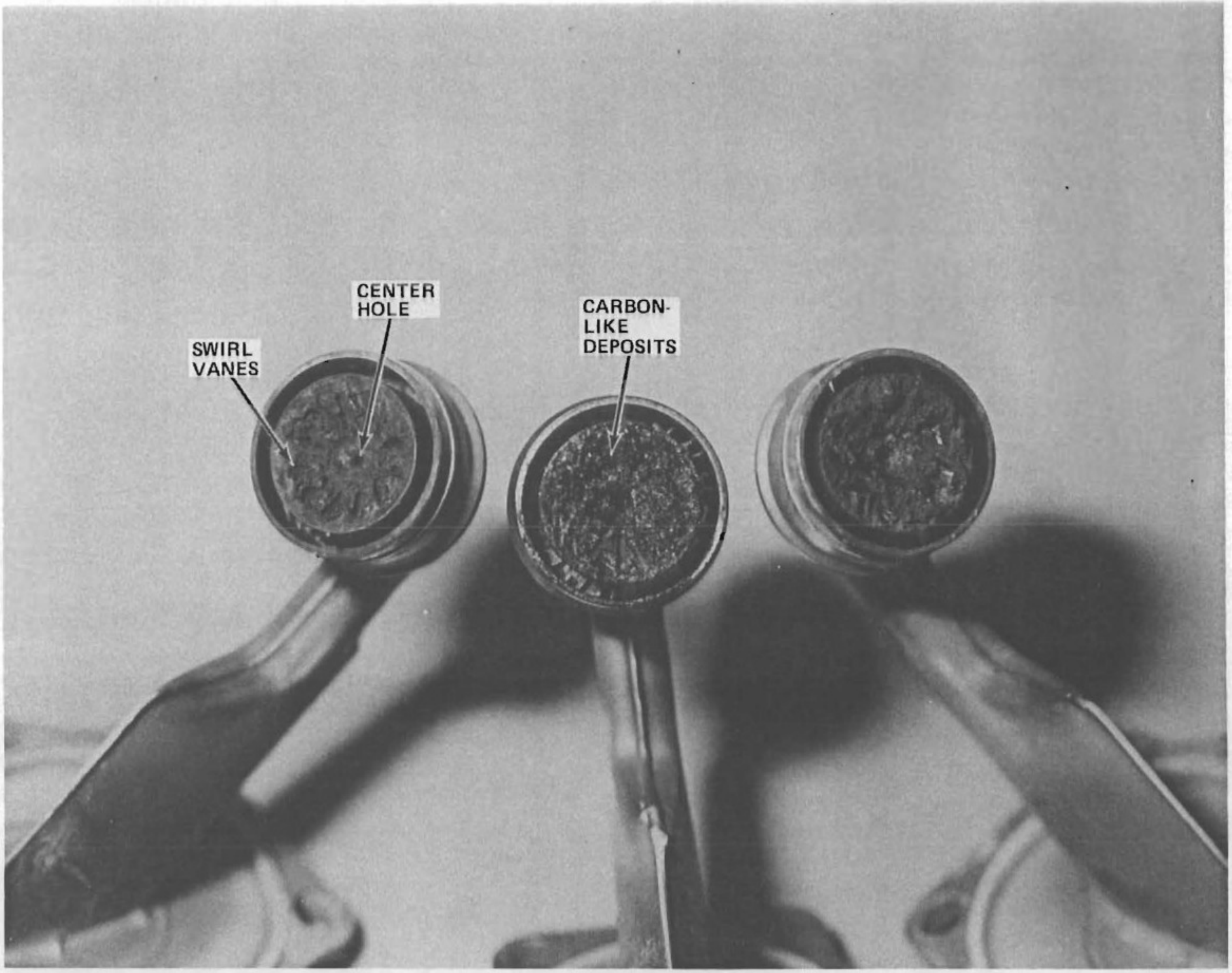

Figure 26. (U) Close-up photograph of fuel nozzles.

12 and 13. Stages 4, 5 and 10 are tighter than they need to be, but that is not harmful to the performance of the machine. If anything, the closer tip gap probably helped to improve the performance of the machine.

[redacted] Figure 27 is a photograph of the 13th stage compressor rotor. The leading edge is highly polished and some material has been removed at about 70% span near the leading edge. The increase in tip clearance appears to have been mainly due to removal of the abradable shroud material as opposed to removal of material from the blade tip. The blade tips for this machine look much better than those of the machine described in Reference 1. By looking much better is meant that the tip has not been significantly thinned by material removal and that the profile has not been substantially changed by material removal. Figure 28 is a photograph of the 11th stage compressor blade tip which when compared to Figure 39 of Reference 1 illustrates the point just made.

Table 5. (U) Compressor tip clearances measured during teardown compared to allowable values.

Stage No.	Allowable min, in.	Allowable max, in.	Actual Measurement in.
4	0.0540	0.0670	0.0315
5	0.0485	0.0615	0.0207
6	0.0225	0.0355	0.0277
7	0.0285	0.0415	0.0375
8	0.0355	0.0485	0.0450
9	0.0235	0.0365	0.0410
10	0.0245	0.0375	0.0215
11	0.0205	0.0335	0.0280
12	0.0215	0.0345	0.0482
13	0.0165	0.0295	0.0517

[redacted]

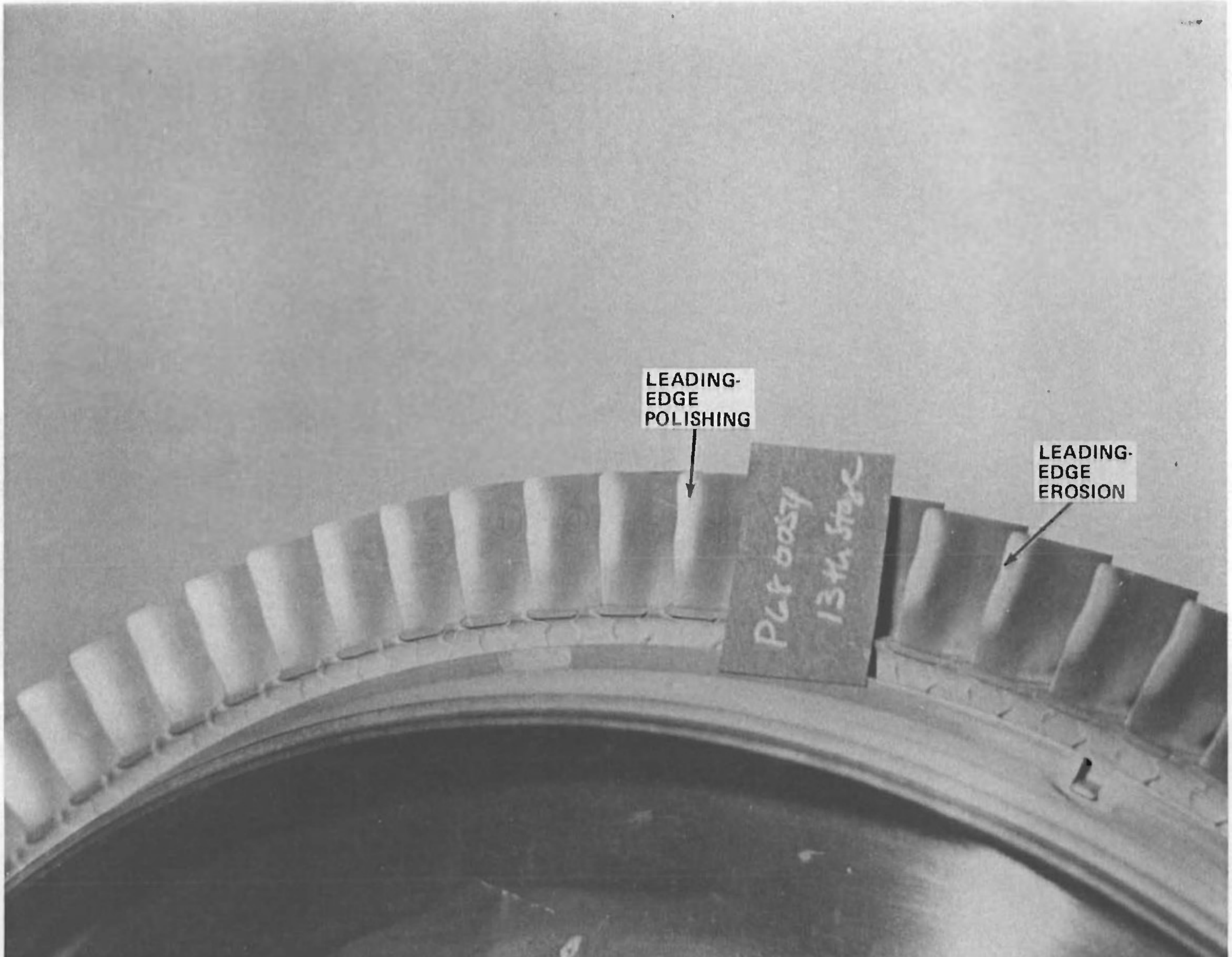

Figure 27. (U) Photograph of 13th stage compressor rotor.

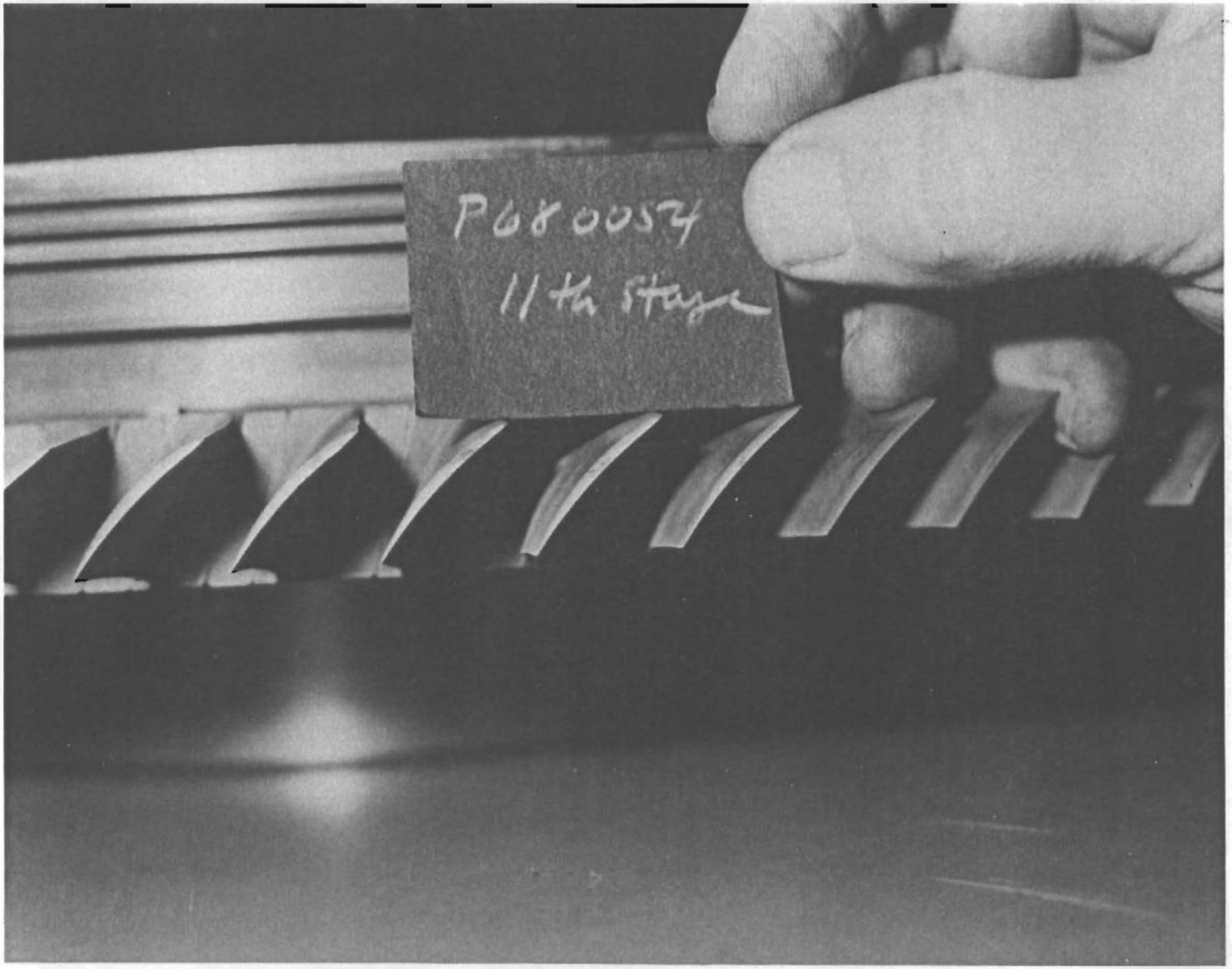

Figure 28. (U) Photograph of 11th stage compressor rotor blade tip region. [redacted]

[redacted] Figure 29 is a photograph of the 12th stage compressor rotor. This stage looks very similar to the stage shown in Figure 27. There is no discoloration of the blades as was observed with the previous engine (see Reference 1). A close look at the tip region of this rotor indicates that tip erosion is very small. Once again, the increase in tip clearance is primarily due to erosion of the abradable seal and not the blade tip.

[redacted] Figures 30 through 33 are photographs of the 7th, 6th, 5th and 4th stages of the high-pressure compressor, respectively. Some polishing and a small amount of material removal can be seen on the leading edge near the top. The tip region of these blades all appear to be in excellent shape. In addition, the abardable seals for these stages were also in excellent shape.

[redacted] The fan section of the second engine was undamaged by the dust material. The fan blades were polished but there was no visible erosion. This is in direct contrast with the results of the first F100 engine (see Reference 1) for which the fan section sustained considerable damage.

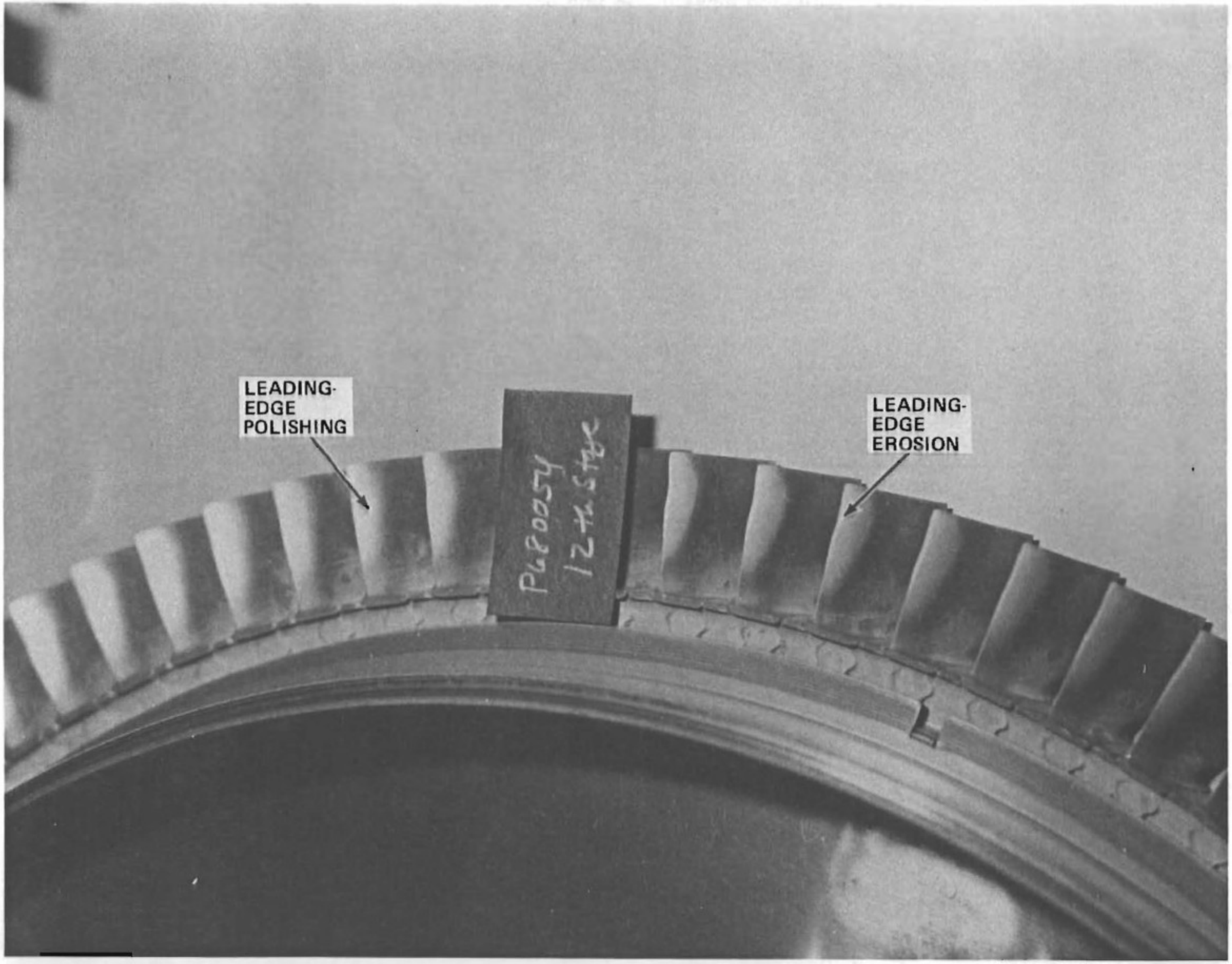

Figure 29. (U) Photograph of 12th stage compressor rotor.

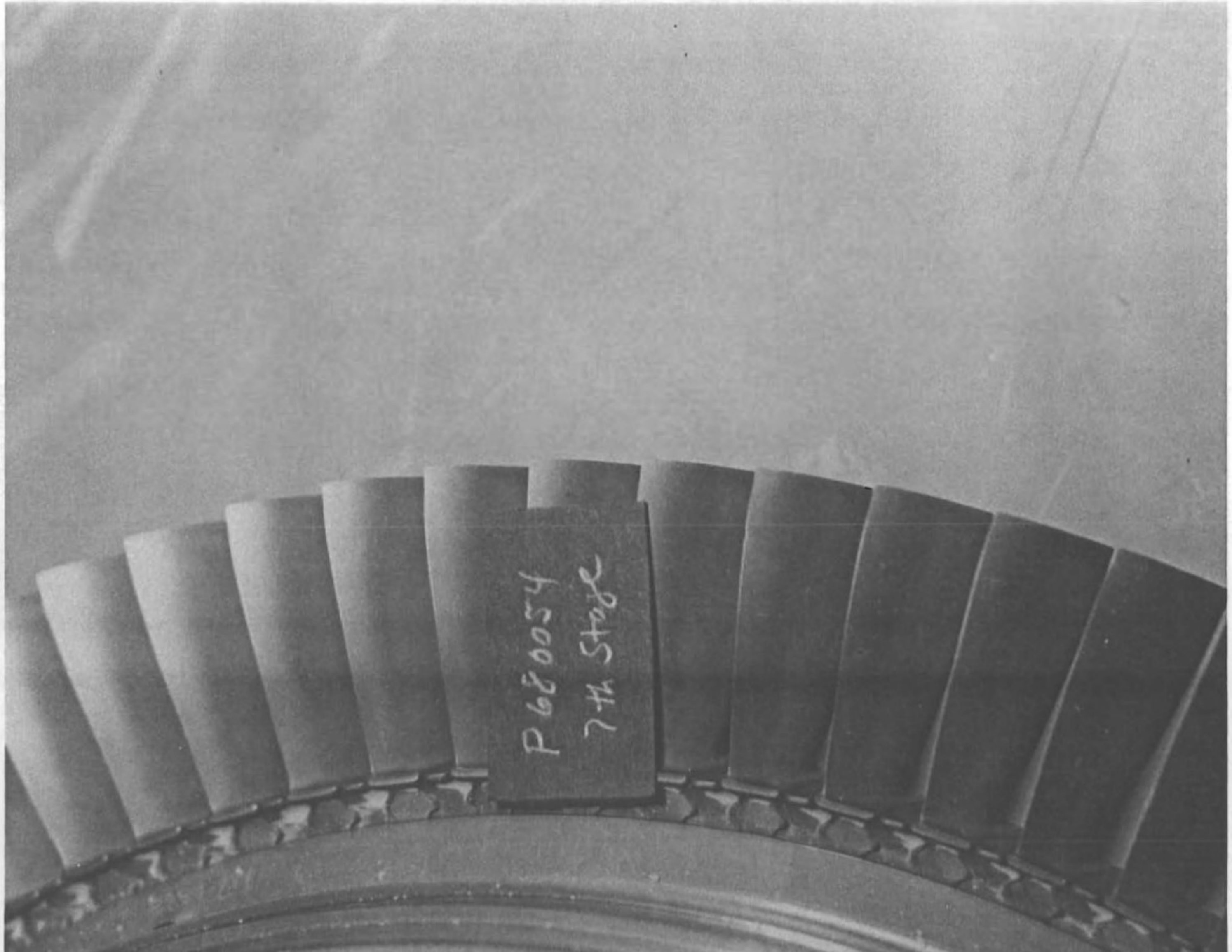

Figure 30. (U) Photograph of 7th stage compressor rotor.

[redacted]

Figure 31. (U) Photograph of 6th stage compressor rotor.

Figure 32. (U) Photograph of 5th stage compressor rotor.

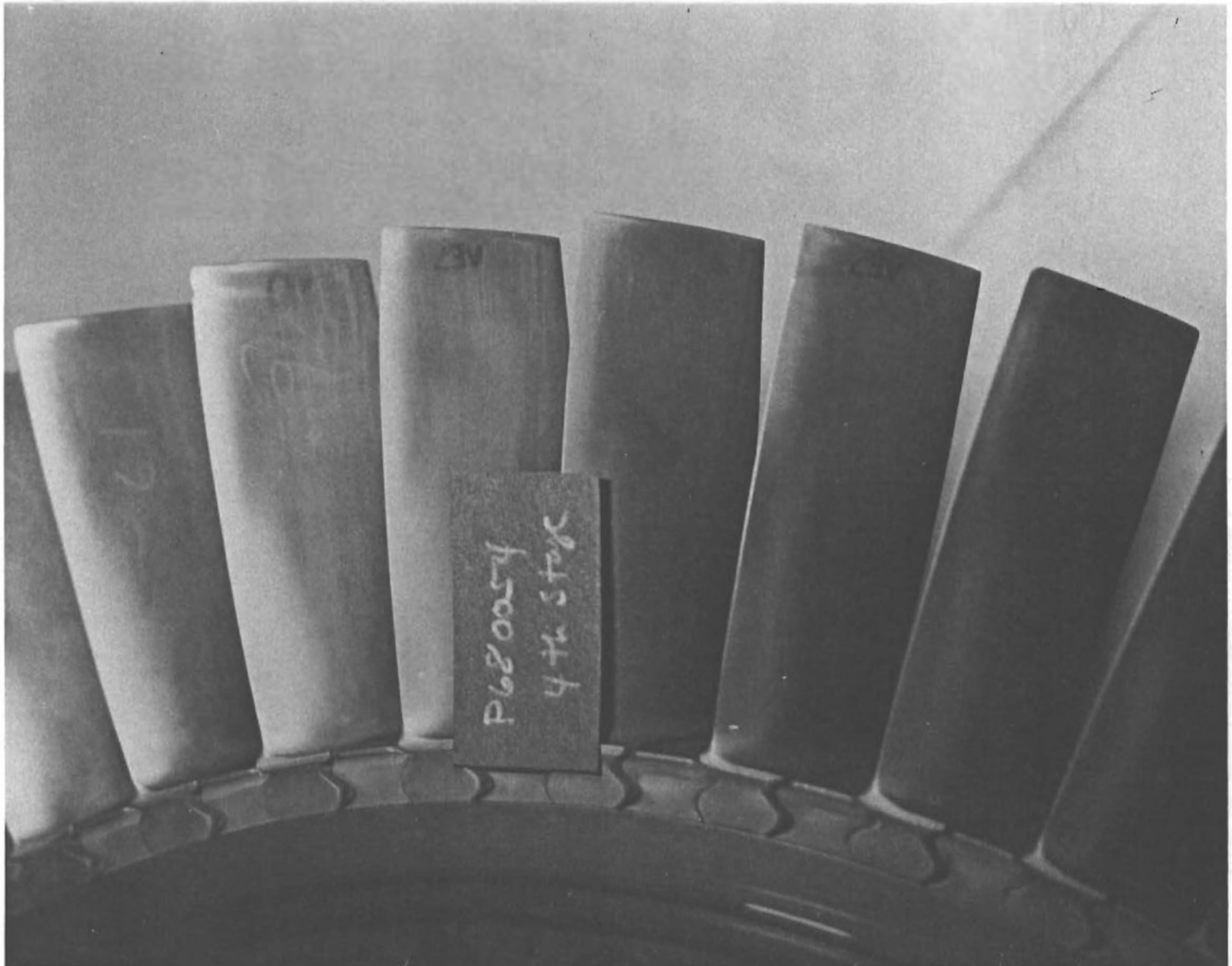

Figure 33. (U) Photograph of 4th stage compressor rotor.

Section 4
(U) CONCLUSIONS AND RECOMMENDATIONS

[redacted] Results of a laboratory measurement program have been described in this report for a Pratt/Whitney F100-100 turbofan engine which was subjected to a simulated nuclear dust environment. The engine was operated at a relatively high thrust setting (with a corresponding turbine inlet temperature in the vicinity of 2485°F) and was subjected to a dust cloud concentration of 500 mg/M^3 (5×10^{-7} gm/cm^3). Both the thrust setting and the dust concentration represent reasonable operational points on a typical approach flight path. The engine remained operational for an exposure time of 20.5 minutes during which it ingested 43.19 kg of dust material. While trying to clear the engine of deposited material at 20.5 minutes into the dust exposure, the engine went into an uncontrollable surge mode and it was necessary to shut off the fuel supply in order to regain control. It was not possible to restart the engine after the event just described.

(U) On the basis of the material presented in this report the following conclusions have been drawn:

1) [redacted] For the engine operating conditions of this experiment, the principal damage modes to the engine are (a) deposition of glassified material on the first stage high-pressure turbine nozzle guide vanes (NGV's), which significantly restricts the flow area, (b) deposition of a carbon-like material on the fuel nozzles which is felt to have drastically altered the fuel spray pattern, and (c) deposition of a very hard material in the NGV of the second stage of the high-pressure turbine, which may or may not have had a direct influence on the engine operation.

2) [redacted] The glassy material deposited on the NGV's was successfully cleared twice by rapid throttle movement (from cruise to idle and back to cruise). A video camera view of the tail pipe during these throttle excursions showed material exiting the engine. The third attempt at clearing the engine in this manner resulted in the surge condition described in the opening paragraph of this section.

3) [redacted] The glassy material deposited on the first stage NGV of the high-pressure turbine becomes brittle as it cools and does not adhere tightly to the metal surface of the vane.

4) [redacted] Damage to the compressor and fan stages of the machine was very minor for the operating conditions of this experiment. Only the final two stages (12 and 13) of the high-pressure compressor suffered any damage and that damage was primarily to the tip rub strip.

5) [redacted] The engine parameters that provide the earliest indicators of glassification within the engine and the manner in which they respond, are as follows:

a. A rapidly increasing burner static pressure (P_b).
b. A rapidly increasing compressor discharge static pressure (P_{s_3}).
c. A rapidly increasing fan turbine inlet temperature (FTIT).
d. A rapidly increasing engine pressure ratio (EPR).
e. A noticeable increase in fuel consumption (w_f).
f. The dust material causes St. Elmo's glow to immediately appear at the fan face.

(U) On the basis of experience gained by performing this measurement program for the two F100-100 engines it is recommended that:

1) [redacted] As soon as St. Elmo's fire appears on the wind screen or the glow is observed at the fan face, the engine thrust should be reduced as much as possible in order to reduce the turbine inlet temperature below 2200°F if possible. The engine can ingest somewhat more dust material (at least 35% to 50% more) at a lower thrust level without catastrophic damage than it can at the higher thrust levels. Looking at the situation a little differently, it takes longer to severely damage the engine by the erosion mechanism (engine #1, see Reference 1) than it does to severely damage the engine by deposition (this engine).

2) ● The engine readout parameters should be monitored very carefully and when the burner pressure, the fan turbine inlet temperature, or the compressor discharge pressure increase significantly the throttle should be cycled to clear the deposited material. We recommend a relatively slow throttle movement and not a rapid movement as was used here. By slow, we mean cruise to idle in maybe 12 seconds and back to cruise in another 12 seconds. Further, only one engine should be cleared at a time.

3) ● The operator should become very familiar with the operation of the engine control system for his particular engine. As damage to the components becomes more extensive, the control system takes over and attempts to protect the engine. If the operator doesn't recognize the dusty environment, or if he is unfamiliar with the control system operation, or if he doesn't know which of the engine parameters to monitor, then the result can be an engine shut down. If the fuel nozzles have not been damaged by deposition of the carbon-like material shown herein, then it will probably be possible to restart the engine after the hot section components cool and the deposited material breaks up. For both cases in which the fuel nozzles were carbonized in our experiments, it was not possible to restart the engine.

SECTION 5

(This List is Unclassified)

LIST OF CLASSIFICATION GUIDANCE REFERENCES

1. Security Classification Guide for F-15 Tactical Fighter (Eagle), dated 15 October 1986, (UNCLASSIFIED).

2. F-16 Multimission Fighter Security Classification Guide, dated 20 June 1986, (UNCLASSIFIED).

3. Security Classification Guide B-1B Program, dated 31 October 1984, (UNCLASSIFIED).

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